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Assessing climate change impact on Guyana's crops using integrated crop and spatial modeling approaches

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Assessing climate change impact on Guyana's crops using integrated crop and spatial modeling approaches

Project: Development of an Evidence-Based, Gender Equitable Framework for Climate-Smart Agriculture Interventions

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Abbreviations and acronyms

CAM	Crassulacean acid metabolism
CHIRPS	Climate Hazards group Infrared Precipitation with Stations
DAPA	CIAT Decision and Policy Analysis Program
DPI	Department of Public Information
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross domestic product
GLSC	Guyana Lands and Surveys Commission
GRDB	Guyana Rice Development Board
GRPA	Guyana Rice Producers Association
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
MICE	Multiple Imputation by Chained Equation
MMA	Mahaica Mahaicony Abary
MOA	Ministry of Agriculture
NASA	National Aeronautics and Space Administration
NAREI	National Agricultural Research & Extension Institute
RCP	Representative Concentration Pathway
UG	University of Guyana
UNFCCC	United Nations Framework Convention on Climate Change

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1. Background

The Crop and Spatial Modeling activity was part of the project 'Development of an Evidence-Based, Gender Equitable Framework for Climate Smart Agriculture Interventions,' carried out under the Ministry of Agriculture and in collaboration with the International Center for Tropical Agriculture (CIAT), the Hydrometeorological Service of Guyana, and the University of Guyana. The project required geospatial vulnerability assessment and crop modeling research and extends previous climate change studies and vulnerability and capacity assessments regarding Guyana's agricultural sector (GUYSUCO, 2009; Ministry of Agriculture, 2013). The research was completed on the comparative use of geospatial methods and crop modeling tools for modeling crop suitability and yield in Guyana. This report shows thematic map outputs that indicate agro-climatic zones of high to low growth potential using current climate and edaphic datasets. Crop modeling required research of the growing conditions of target crops, after which calibrations were applied to estimate yields under future climate scenarios RCP4.5 and RCP8.5.

This report presents the spatial modeling and crop modeling work undertaken to estimate land suitability and yield, respectively, for the selected crops. It examines the methods and results of the models applied through the course of this project. The respective methodologies applied are first discussed, followed by a presentation of each crop's model results. A general discussion follows that analyses the results and presents the regional outlooks for the target regions. In summary, the models provided critical information on crop productivity at the target regions under historical records and future climate scenarios. The results of this activity can be used to understand how crops will fare in the face of climate change that will likely bring increased and prolonged dry spells and floods to Guyana, determine which crops can thrive in non-traditional growing areas in the future, identify suitable areas for agricultural expansion, and establish field management strategies to reduce losses and maximize crop yield.

The project's primary aim was to enhance the Government of Guyana's capacity to develop evidence-based, gender-equitable plans, and programs to adapt to and mitigate the impact of climate change on the agricultural sector. Modeling allowed vulnerability assessment to cultivate seven priority crops based on historical (near current) and future climates, based on geographical location and yield estimates.

Within this scope, the specific objectives were to:

1. Prepare national secondary datasets and test available crop and spatial models.
2. Conduct integrated modeling of yield and suitability scenarios under future climates.

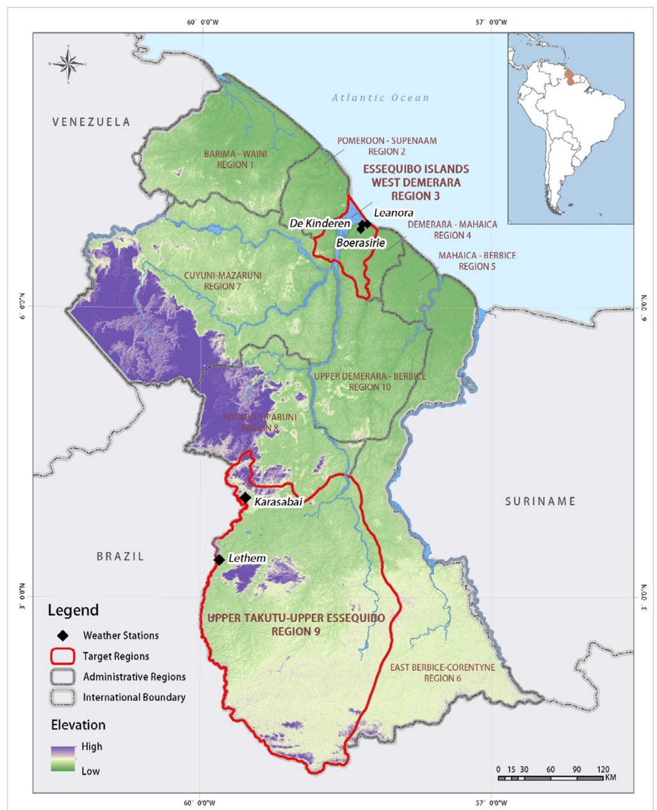

Figure 1 Target Administrative Regions under the Project.

For crop modeling, Essequibo Islands-West Demerara (Region III) represented the target coastal Region under this study, and Upper Takutu – Upper Essequibo (Region IX) represented the target hinterland Region. The geospatial vulnerability assessment was undertaken at the country scale to extend the suitability investigation to all Administrative Regions.

2. Methodology

This section presents the modeling methodologies applied for land suitability and yield forecasting. Land suitability modeling was applied across Guyana, while crop modeling was based on available weather station data for the two target administrative regions identified by the Ministry of Agriculture. Priority crops for these studies (Table 1) were selected through focus group discussions, interviews, and input from the Ministry of Agriculture officials, based on examining agricultural potential through diversification.

Crop	Region III	Region IX
Rice	X	X
Plantain	X	X
Pineapple	X	
Peanut		X
Sweet potato	X	
Coconut	X	X
Cassava	X	X

Table 1. Prioritized crops by Administrative Region.

Representative Concentration Pathways

Representative Concentrative Pathways (RCPs) were used to model climate futures. These are future climate scenarios that model emissions, greenhouse gas concentrations, aerosols, chemically active gases, and land use and land cover (Moss et al., 2008). The term *representative* implies that each RCP provides only one of many possible scenarios that would lead to the future climates modeled. At the same time, *pathway* denotes that long-term concentration levels and their trajectories are used to reach that outcome. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) used RCPs to make climate predictions and projections. Two were selected for this study:

RCP4.5: a stabilization scenario that assumes that global climate policies are applied to sternly limit anthropogenic contributors to greenhouse gas emissions (Thomson et al., 2011). In this scenario, emissions are predicted to decline following a peak around 2040.

RCP8.5: a scenario characterized by increasing greenhouse gas emissions over time, representing scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al., 2007). It is considered a worst-case climate scenario for the planet.

For the crop and suitability modeling, we used a reference daily-climate dataset (1998 to 2018), and an ensemble of future climate scenarios of two Representative Concentration Pathways (RCPs) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), RCP 4.5 and RCP 8.5 for the decade of 2050s (average 2040 to 2070).

2.1. Land Suitability Modeling

Geospatial techniques were applied to delineate suitable areas for the selected crops using the indicator variables: temperature, precipitation, and soil pH. The results would be useful as a guide for evidence-based decision-making to identify possible areas suitable for expanding crop production.

Suitability modeling was achieved through the following primary methodological stages:

1) Spatial data acquisition and data scrubbing of climate datasets;

2) Simulation testing of various suitability models and parameters;

3) Application of selected geospatial tool to generate suitability surfaces; and

4) Statistical classification of output rasters to facilitate comparisons.

Land productivity is heavily influenced by the agroecological zone's geographical characteristics, such as climate, topography, soil type, and land cover. Cropland suitability analysis is an essential method for achieving optimum land resources for sustainable agricultural production that meets the local population's needs.

Baseline datasets were acquired at the country scale to operationalize the spatial study. Climatic and soil data were obtained through global datasets WorldClim (WorldClim, 2019) and Soil Grids (ISRIC, 2019). Soil pH was incorporated with the climate raster to model the availability of essential soil factors (structure, bacteria, nutrients, etc.) needed for crop productivity.

Data	Spatial Resolution	Source
Mean Annual Temperature (°C)	1 km	WorldClim
Total Annual Precipitation (mm)	1 km	WorldClim
Mean Soil pH	1 km	Soil Grids

Table 2. Summary of spatial climate datasets.

Suitability analysis was conducted to identify areas across Guyana with the appropriate agro-climatic conditions to cultivate each of the prioritized crops. Several geospatial methods were tested to achieve this, such as agroecological GIS analysis, suitability scripts, and weighted sum analysis. In the end, the geoprocessing script *Targeting* was selected for this task. Developed by CIAT scientists, this tool is used to detect areas with the best biophysical conditions for a crop to thrive. It first groups raster values suitable for the crop then performs an algebraic function to intersect the raster layers on a suitability scale based on an equal weighting. In the output raster, areas with pixel values that fall outside of the scale were deemed as unsuitable for crop growth; areas with pixels that satisfied the broader range of conditions needed for a crop to thrive were identified as limited condition areas (marginal to moderate suitability), and areas with pixels that satisfied all optimal growth conditions needed for that crop were identified as high suitability areas (Figure 2).

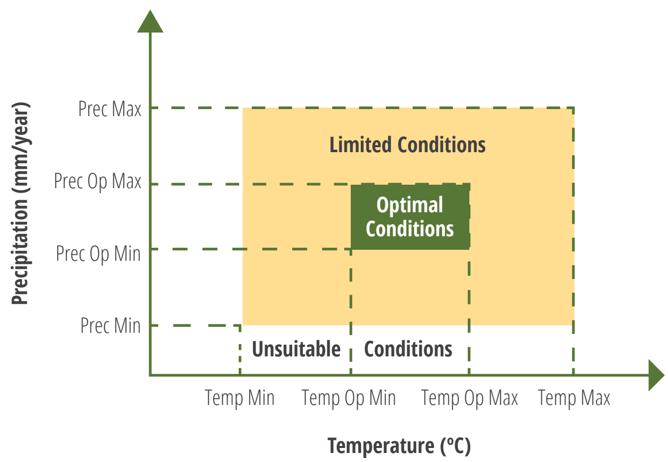

Figure 2 Schematic of Targeting's pixel intersection function to identify optimal growth conditions.

Therefore, the geoprocessing workflow (Figure 3) required numerical inputs of crop growth parameters to operationalize the Targeting Land Suitability tool, according to min/max and optimal growth conditions. This data was extracted from agricultural literature, particularly from NAREI and FAO documents.

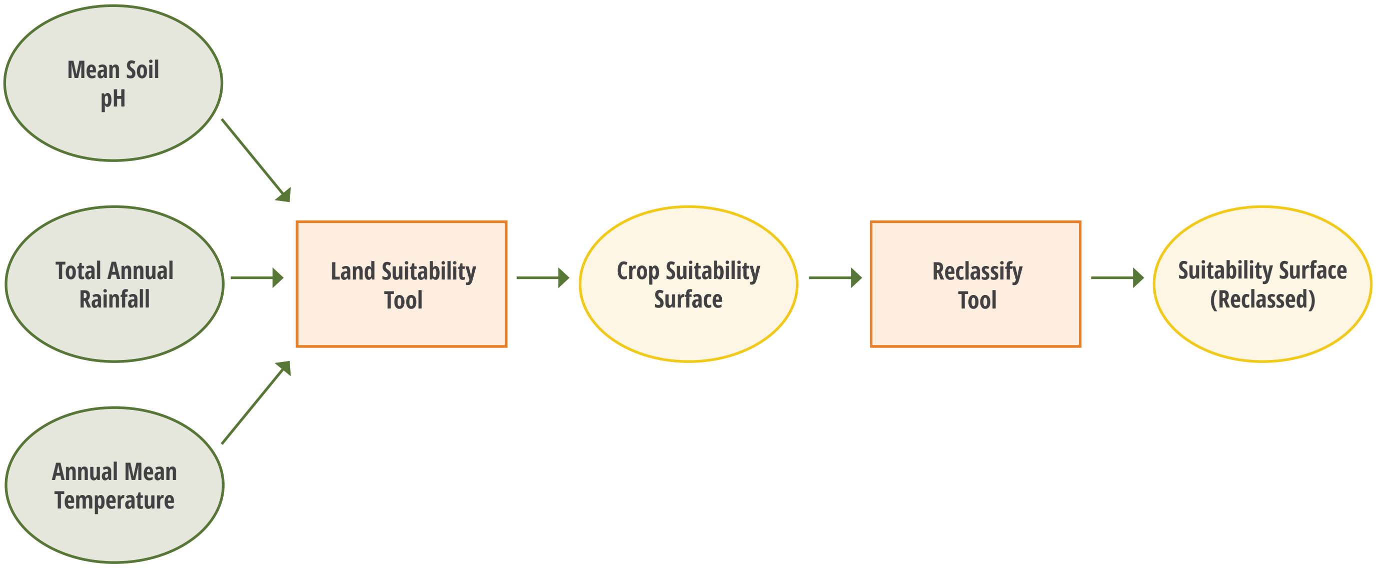

Figure 3 Cartographic model of geoprocessing workflow for suitability surface generation.

The workflow was run on historical (near-current) climate datasets, and then repeated on RCP4.5 and RCP8.5 future climate datasets. According to current and future climates, the final suitability surfaces generated for each crop are presented in forthcoming sections. Cartographic production, particularly concerning classification (color schema and class types), was guided by FAO documentation for agroecological mapping zones (FAO, 1996). The equal interval data classification method was applied for multiple map comparisons across the percentage data ranges. Each map is constructed from different crop parameter inputs.

2.2. Crop Modeling

Crop models are useful as an agronomic research tool that can be used as a decision support system to aid in planning and policy (Steduto et al., 2009a). The application of crop models enables the synthesis of scientific outputs with knowledge on local productivity, which can guide planning towards the benefit of farmers, consumers, and the local economy.

Crop modeling was achieved through several methodological stages, as outlined below:

1. Preparation of daily climate databases for each weather station;
2. Testing various climate model tools to determine appropriateness for crop modeling;
3. Preparation of datasets for AquaCrop simulation; and
4. AquaCrop and R Modeling to output crop yield boxplots.

Climate databases were developed for Regions III and IX, featuring the weather parameters rainfall, maximum temperature, minimum temperature, and solar radiation. A twenty (20) year period (1998-2018) of each parameter's daily data was required to achieve this. Sixteen (16) weather stations were initially selected, with four stations comprising data for the needed parameters during the period 01-01-1998 to 31-12-2018. However, only rainfall data was available for the remaining stations. The large volume of missing data from the datasets presented the need to fill gaps because the crop models require complete datasets, i.e., no missing values. After eliminating stations that were not within the target Regions, five stations were selected to provide comprehensive datasets to generate the simulations. These were the Boerasirie, De Kinderen, Leonora stations at Region III, and the Lethem and Karasabai weather stations at Region IX.

Station Name	Coordinates		Percentage (%) of Missing Data		
	Latitude	Longitude	Rainfall	Maximum Temperature	Minimum Temperature
04GEOBOT	6.8064	-58.1452	**0.0**	**2.164**	**1.604**
06NATIII	6.2431	-57.5137	**0.0**	**2.894**	**0.652**
09LETHEM	3.3667	-59.8	**0.365**	**0.274**	**0.652**
02AANRG	7.255	-58.492	**1.408**		
03BAGLEG	6.917	-58.417	**12.712**		
03BOERAS	6.8167	-58.35	**0.834**		
04CGROVB	6.6167	-57.833	**5.984**		
03DEKENF	6.8333	-58.316	**6.897**		
02CAPOEY	7.203	-58.497	**16.728**		
02ODENMG	7.1	-58.4667	**3.755**		
02WAKPOW	7.5833	-59.75	**8.018**		
03DEKENB	6.8667	-58.3333	**6.897**		
03FORTIL	6.7833	-58.5	**8.175**		
03HOGILS	6.8667	-58.5167	**16.923**		
03LNORAB	6.87	-58.2834	**4.407**		
03UIVLBK	6.8	-58.3167	**11.330**		
04KYRUNI	6.15	-58.2333	**24.524**		
04GHOPEC	6.62	-58.0872	**12.829**		
04TIMAIR	6.4923	-58.2523	**28.031**		
05BLMONT	6.25	-57.5333	**2.816**		
06ALBN33	6.2333	-57.3833	**6.571**		
06SKELDF	5.8833	-57.1333	**13.025**		
07KAMRNG	5.8833	-60.6167	**6.571**		
09KARSAB	4.0333	-59.5333	**5.776**		
10EBINII	5.6422	-57.7715	**2.738**		

NASA power data reviewer and MICE imputations were used to fill missing data. Some stations only have rainfall or temperature data and are missing for most of the study period.

TABLE KEY:

Target Stations

Table 3. Climate data availability at local weather stations: 1998–2018.

The statistical analysis tool, *RClimtool*, was used to fill missing gaps in these datasets. Among this tool's objectives, RClimtool was designed to facilitate the performance of statistical analysis and fill missing data. RClimtool only works if data are within the same time frame, i.e., begins on the same year, month, and same-day and ends on the same year, month, and day. Therefore, quality control was done to eliminate data viewed as outliers or errors due to incorrect input of the data in the file set or human error in reading of the weather instruments. Following this approach enabled climatologically accurate data for the locations selected across Guyana.

Due to the inability of the precipitation package of RClimtool to generate files for missing rainfall data, only the Maximum and Minimum Temperatures were filled using RClimtool. Other tools explored to fill missing rainfall data included CHIRPS data, NASA Power Data Reviewer, and Multiple Imputation by Chained Equations (MICE) data. Through testing, NASA Power Data Reviewer and MICE were determined as the best options for this task since both methods returned values within the normal climatological range at the locations.

Crop Model Selection

AquaCrop and *CropWat* were tested to compare current yield production to future yield production for Regions III and IX as it relates to changes in climate and climate variability. AquaCrop was eventually selected to generate crop yields for this project. It is a crop water productivity model developed by the FAO to improve water productivity in rainfed and irrigated fields. The model simulates yield response to water of herbaceous crops and calculates yield as the biomass and harvest index (Steduto et al., 2009b). Its focus on water is relevant in the face of depleted water resources and dependency on water for agricultural production. AquaCrop is particularly suited to address conditions where water is a critical limiting factor in crop production and has been used in different agroecological conditions worldwide.

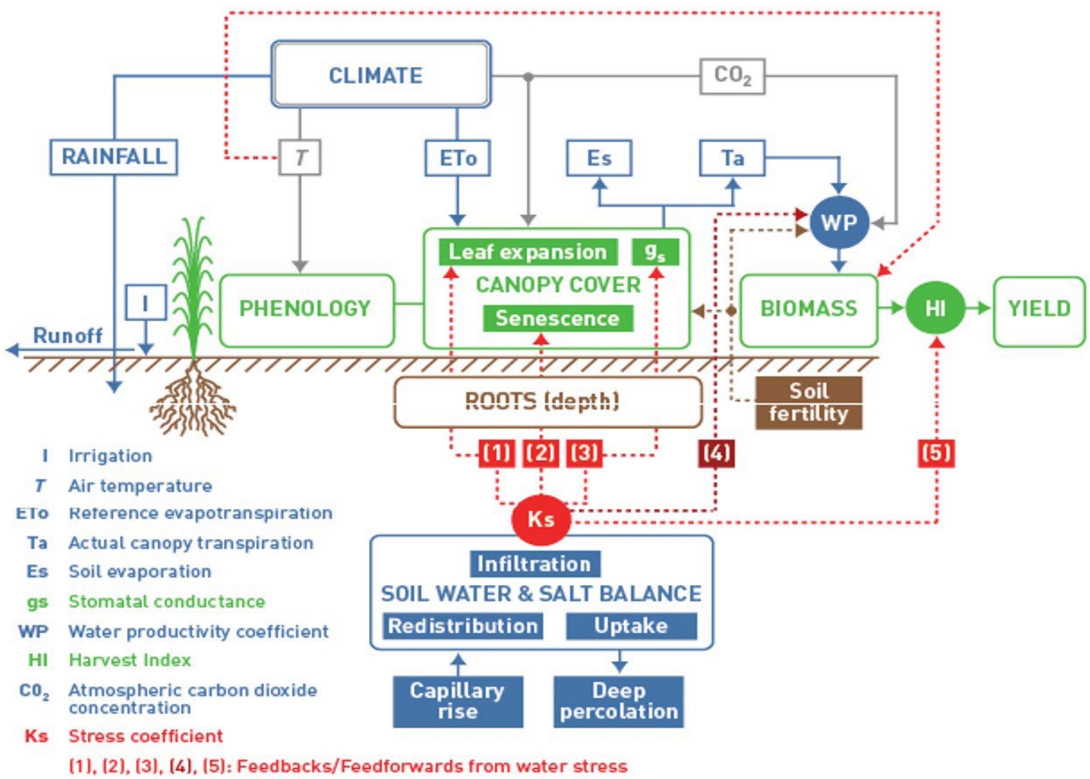

Figure 4 AquaCrop flowchart indicating components of the soil-plant-atmosphere continuum.

AquaCrop was used to simulate different conditions for several crops grown in Guyana. Yield scenarios were simulated for rainfed and irrigated conditions based on the reference climate data at each location. Future yields were then simulated using daily climatic data generated from global climate models from 01-01-2040 to 31-12-2070. We used RCP4.5 and RCP8.5 and applied the Quantile Mapping bias-correction method. Climate data were applied from the climate databases developed for the Boerasirie, De Kinderen, and Leonora weather stations at Region III; and the Lethem and Karasabai weather stations at Region IX. Crop data were inputted with soil data for the specific areas. Field management practices and irrigation methods were then calibrated to run the simulations (Hsaio et al., 2009; Raes et al., 2009).

2.3. Model Enhancement and Analyses

Both land suitability and crop modeling required dozens of iterations for each crop to derive the results presented in this report. Iterations were simulated based on adjustments to refine input parameters, weighting, and testing of water responses and climate scenarios. Finally, analyses were formed against information from technical reports, scientific papers, and other literature on the target crops; and local knowledge data derived through interviews with farmers and technical officers.

2.4. Limitations

The following limitations must be noted in the interpretation of the model results.

FOR SPATIAL MODELING

Three variables (total precipitation, mean temperature, soil pH) were applied to model land suitability for each crop. The output suitability surfaces, therefore, provide broad scenarios across the landscape. It is important to note that suitability may also vary based on soil type, soil moisture, relief, land use and land cover, tenure, degradation, and access considerations (GFA Terra Systems, 2003). The models help discern land suitability change (over time) and variation (across space) for each crop. However, they do not cater to other factors that may constrain suitability. Therefore if a crop is under consideration for a particular location, these results should be adjusted based on physiographic, land use, and other characteristics specific to that area.

Soil pH is kept steady in future scenarios. While it is recognized that this variable could change in the future (due to saltwater intrusion, groundwater dynamics, fertilizer buildup, and other potential salinization events), the current pH is used as an indicator absence of future pH data.

Spatial suitability is indicated for rainfed conditions but does not account for crop irrigation practices. Suitable areas for certain crops may therefore increase under irrigated conditions.

FOR CROP MODELING

Complete weather data for the 1998-2018 reference period were not available for all weather stations in the target Regions. At Region IX, the nation's largest administrative region by geographic area, datasets were only available for Lethem and Karasabai in the Central Rupununi and South Pakaraima Sub Districts. This is particularly limiting as weather conditions vary across Region IX. Therefore, yield estimates for other Region IX locations should be based on projections at the proximal modeled village, combined with local and expert knowledge of village microclimates.

Detailed local data on crop growth stages were required to ensure the accuracy of the simulations. However, they could not be acquired during this work. Some yield simulations were therefore derived based on generic crop growth data (rather than cultivar-specific data).

AquaCrop modeling does not account for the effect of crop pests and diseases on yield (Steduto et al., 2009b). Therefore, interpretation of the yield estimates may need to be adjusted based on historical pest and disease impacts on productivity within certain agro-ecosystems.

3. Model Results

This section describes the results of geospatial and crop vulnerability models for each priority crop. Spatial suitability is first presented for the reference climate compared with the RCP4.5 and RCP8.5 future climate scenarios across Guyana. Yield projections from AquaCrop simulations are then presented on the target Regions. A brief discussion follows each sub-section to examine the model results against historical growing patterns, yields, and industry challenges. As coconut was the only crop that could not be modeled to derive future yield[1], a broader discussion examines its potential productivity based on the subject literature, phenological characteristics, and climate change scenarios.

3.1 Rice Models

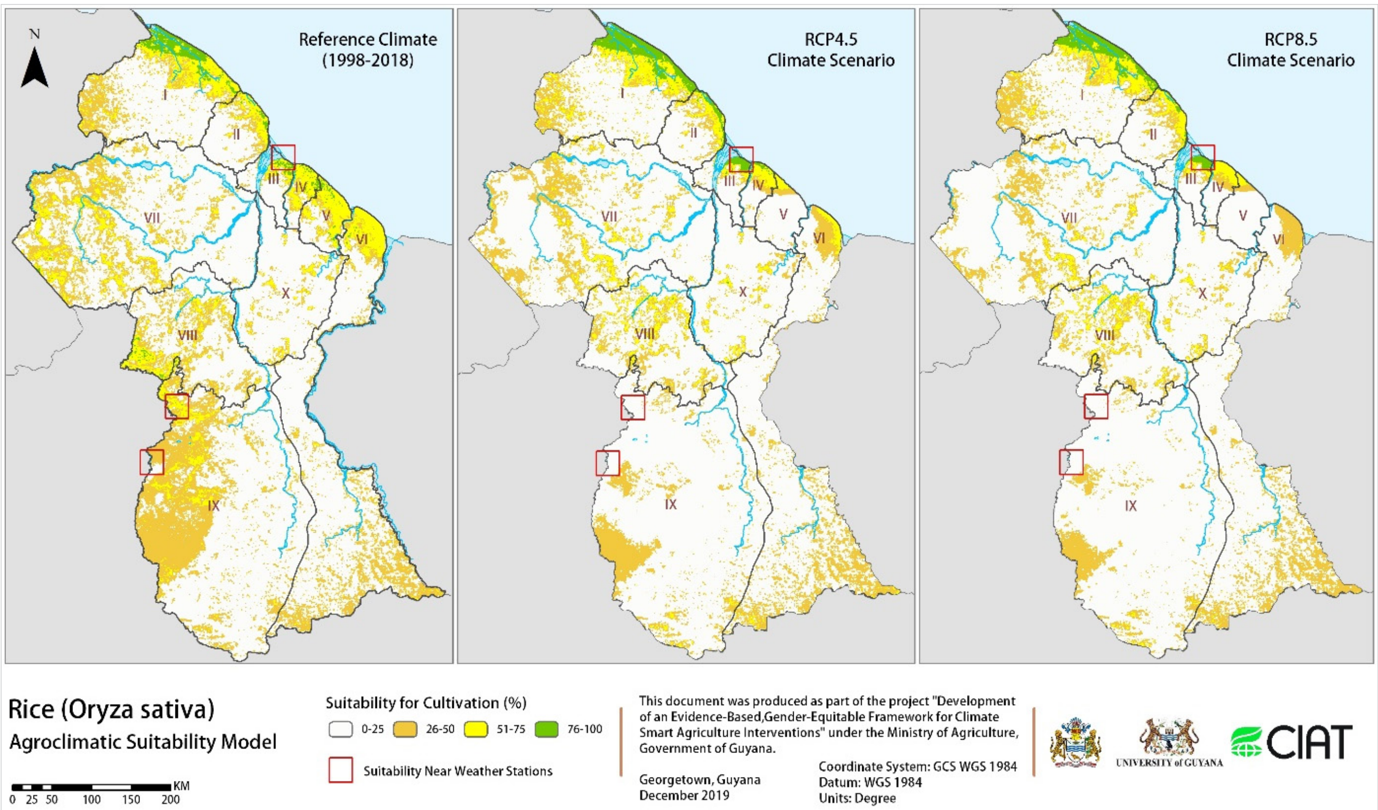

Figure 5 Spatial Suitability for Rice: Reference (left) and Future Climates.

3.1.1. Spatial Modeling Trends

Reference Climate

The agro-climatic suitability model for rice cultivation indicates the low-lying coastal strip as having an ideal climate for this crop, highlighting the current major rice-growing areas in Guyana from Regions II to V. Rice farming benefits from seasonal variations and coastal drainage and irrigation system of the flatlands. Moderate suitability is also derived in pockets in the country's interior, most notably in the areas of the Pakaraimas (southwest areas of Region VIII and the north Rupununi sub-district). While rice cultivation does not occur in Region VIII, the Santa Fe Megafarm produces rice in the North Rupununi.

1 Crop modeling could only be undertaken for herbaceous crops.

Other administrative regions modeled indicate mainly low or marginal suitability (0-50%) for rice cultivation based on the input parameters, since rainfall amounts, temperatures, and soil pH vary from that of the coast. It is worth noting that the model highlighted the apex of Guyana as an area of high suitability for rice cultivation. However, this zone forms part of the Shell Beach Protected Area for nesting marine turtles. Farming in this area is typically for subsistence and cash cropping by the small populations who reside there and is not cultivated for rice.

Future Climate

Future modeling for rice suitability presents some notable changes compared to the current climate. The future climate scenarios particularly favor Region III, as more areas are expected to comprise high suitability under future climate conditions. However, the overall trend indicates that with rising temperatures and more intense rainfall events, more country sections may become less suitable for growing rice. This is particularly evident in coastal Regions 4, 5, and 6, where modeled suitability is reduced to a narrow strip near the coastline and drops by one level; and Regions VII, VIII, and IX for the interior regions. North and Central Rupununi in Region IX, previously highlighted as potential rice expansion areas under current conditions, are projected to experience unfavorable climate to sustain rice cultivation in the long term under the RCP4.5 and RCP8.5 scenarios.

Taking into consideration that the agro-climatic suitability model is run under rainfed conditions, having access to irrigation might still make rice production a valid option for some of these areas showing decreasing suitability. However, climate change carries also new risks for rice farmers, like salt-water intrusion in low-lying coastal areas, and increased risk for pest and diseases due to changing environmental conditions.

3.1.2. Crop Modeling Trends

To better study potential rice yields at the target Regions, yields for the cultivar GRDB-15 were simulated in AquaCrop with six (6) planting days starting from April 15 to June 30, with 15-day intervals. Simulations were run for three locations in Region III and two locations in Region IX. Data on this crop's characteristics were inputted in the model and historical climate data, soil data for the locations under study, and field management practices and irrigation methods at each location.

The results indicated yields between 7 and 8 tons per hectare from a crop cycle averaging 100 days in Regions III and IX. These results are for both rainfed, irrigated conditions, and based on data for the period 1998-2018. Higher yields – though with more significant variability – were forecasted for Region IX than for Region III in both future climate scenarios, averaging 8.5-10.5 tons per hectare (against lower yields of 7.5 tons per hectare for the 1998-2018 reference period). This is probably due to small increases in rainfall at the two locations under future climate projections.

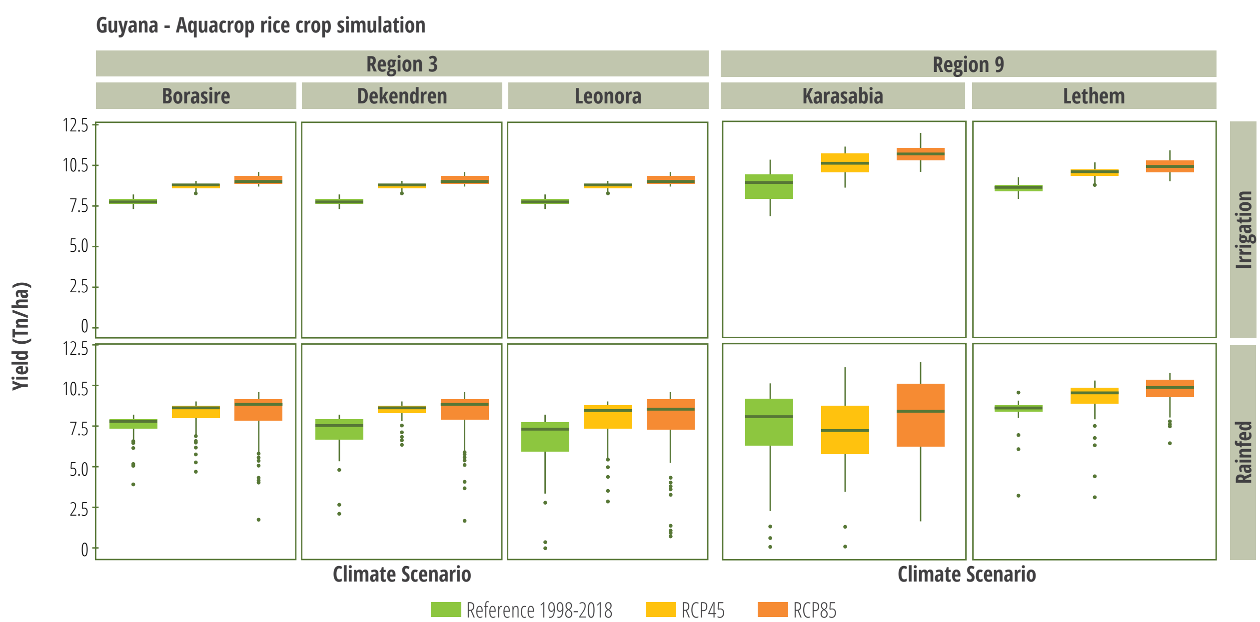

Figure 6 Yield Projections for Rice at Region III (left) and Region IX (right).

Region III Model Results

The localities in Essequibo Islands-West Demerara (Region III) – Boerasirie, De Kinderen, and Leonora – returned yields averaging 7.5 tons per hectare for the 1998-2018 reference period. Future climate scenarios RCP4.5 and RCP8.5 simulate higher yields, averaging 9 tons per hectare in irrigated and rainfed conditions. The RCP8.5 scenario, which considers increasing greenhouse emissions over time, consistently returned the highest yields across the three locations studied. Climate conditions at Region III are projected to become more favorable for rice cultivation over time. The overall spatial extent for cultivation should remain constant. Increased yields are therefore expected from this Region if productive lands continue to be exploited. Given that rice cultivation in Guyana is typically done by small to medium-scale farmers, they benefit from trialing new rice varieties and training in contemporary techniques if more agricultural lands are made available.

Approximately 80% of Guyana's population is settled on the coast. Spatial modeling suggests that some inland areas of coastal regions, such as Regions IV and V, favor rice cultivation under present-day conditions. However, a notable decline in this spatial extent is expected in future scenarios and may impact yield. Poorly maintained coastal drainage and irrigation systems can adversely affect the sector and may be exacerbated by intense drought and flood events.

Region IX Model Results

For the two villages in Upper Takutu – Upper Essequibo (Region IX) – Karasabai and Lethem – both returned yields averaging 8 tons per hectare for the 1998-2018 reference period. Under irrigated conditions, RCP4.5 and RCP8.5 returned yields averaging 10 tons per hectare at Karasabai and Lethem. Under rainfed conditions, yields of between 7.5 and 9.5 tons per hectare were simulated for the two locations in the Rupununi. However, simulations for Karasabai were predicted to have higher variability than at Lethem.

Of note are the hinterland areas where rice cultivation may succeed under present-day conditions with irrigation, such as the North and Central Rupununi of Region IX. Although the Region experiences seasonal drought and flood events, continued research into hardier rice varieties should facilitate understanding of this staple crop's productivity. Climate change may otherwise obstruct its long-term sustainability in this agroecosystem in the absence of newer technologies, which may compromise investments for such developments.

3.1.3. Summary

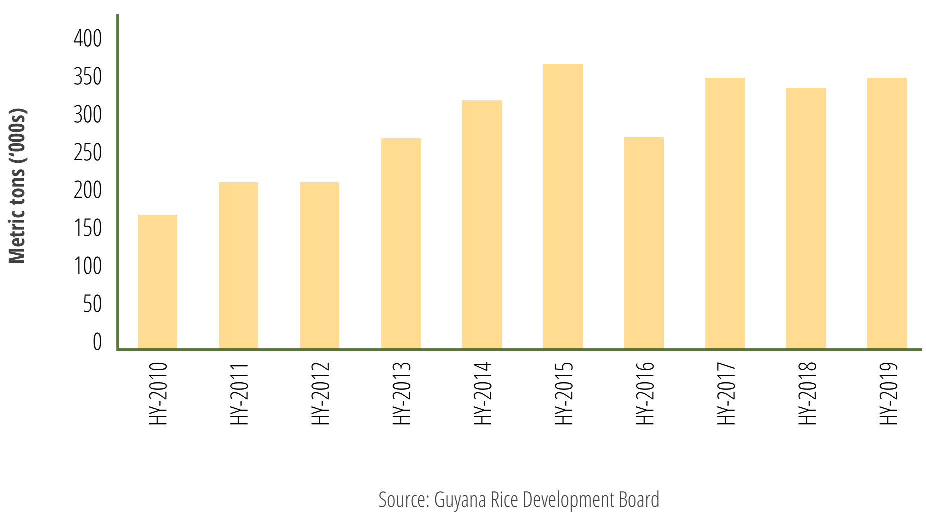

Figure 7 Rice Production (metric tons) 2010-2019.

The spatial suitability model for rice cultivation under current conditions resembles the existing rice growing trends across Guyana. National rice production has increased steadily over the past decade (Figure 7). It is attributed to improved varieties, farming practices, and pest and disease control measures. Such practices have positively contributed to the sector's production profile despite varied weather patterns during the past decade. Guyana's latest rice yields for the first half of 2019 averaged six metric tons per hectare. As described in the Mid-Year Report (Ministry of Finance, 2019), this is reportedly the highest mean yield on record despite the threat of paddy bug infestation. Increased production yields were attributed to:

a) More harvested lands in Regions IV, V, and VI; and
b) Introduction of the new paddy variety GRDB-15 to local growers.

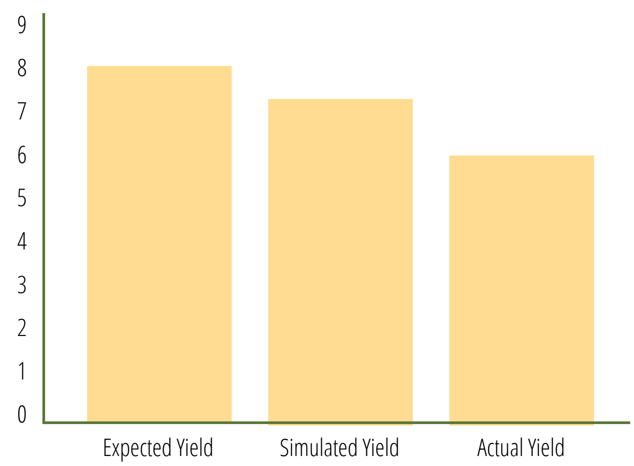

Figure 8 Yield comparisons for rice production in 2019 (t/ha).

The Guyana Rice Development Board released the GRDB-15 cultivar in April 2018 with optimistic yield projections of 8 tons per hectare once cultivation guidelines were followed (Ministry of Finance, 2018). It is described as a long-grained variety with good germination characteristics, low to moderate blacktip, and brown spots. It thrives in delayed harvesting conditions (Guyana Chronicle, 2018). The AquaCrop model simulations for rice were based on the GRDB-15 cultivar's phenological characteristics, as the Ministry of Agriculture expects growers to embrace this high yield variety ("GRDB-15 rice variety yield", Guyana Chronicle, 2018). Accounting roughly for reduced yields likely caused by paddy bug infestations[2], actual rice production yields for early 2019 (based on GRDB-15 and previous cultivars) align reasonably well with simulated mean yields. (Figure 8). However, rice farmers report reduced yields due to the saline intrusion that reaches far into the paddy fields and paddy bug infestations during the dry season. These issues can reduce the yield of 20-25 bags per acre, down from 35-40 bags per acre from a good harvest. Additionally, some rice farmers noted that they continue to use the GRDB-10 variety because of 'wind paddy' (undeveloped endosperm) affecting GRDB-15 harvests.

The spatial modeling considers suitability under rainfed conditions only. AquaCrop modeling contributes important yield projections under irrigated conditions. It forecasts that rice farmers in Regions III and IX stand to benefit from good yields under both rainfed and irrigated conditions by 2050. Although the spatial modeling cautions that the geographic extent for suitable rice-growing lands could diminish in Region IX in the future climate, yields per hectare may remain high within areas that retain suitability.

2 AquaCrop does not account for variables such as pests, diseases and weeds (Steduto et al., 2009b).

3.2. Plantain Models

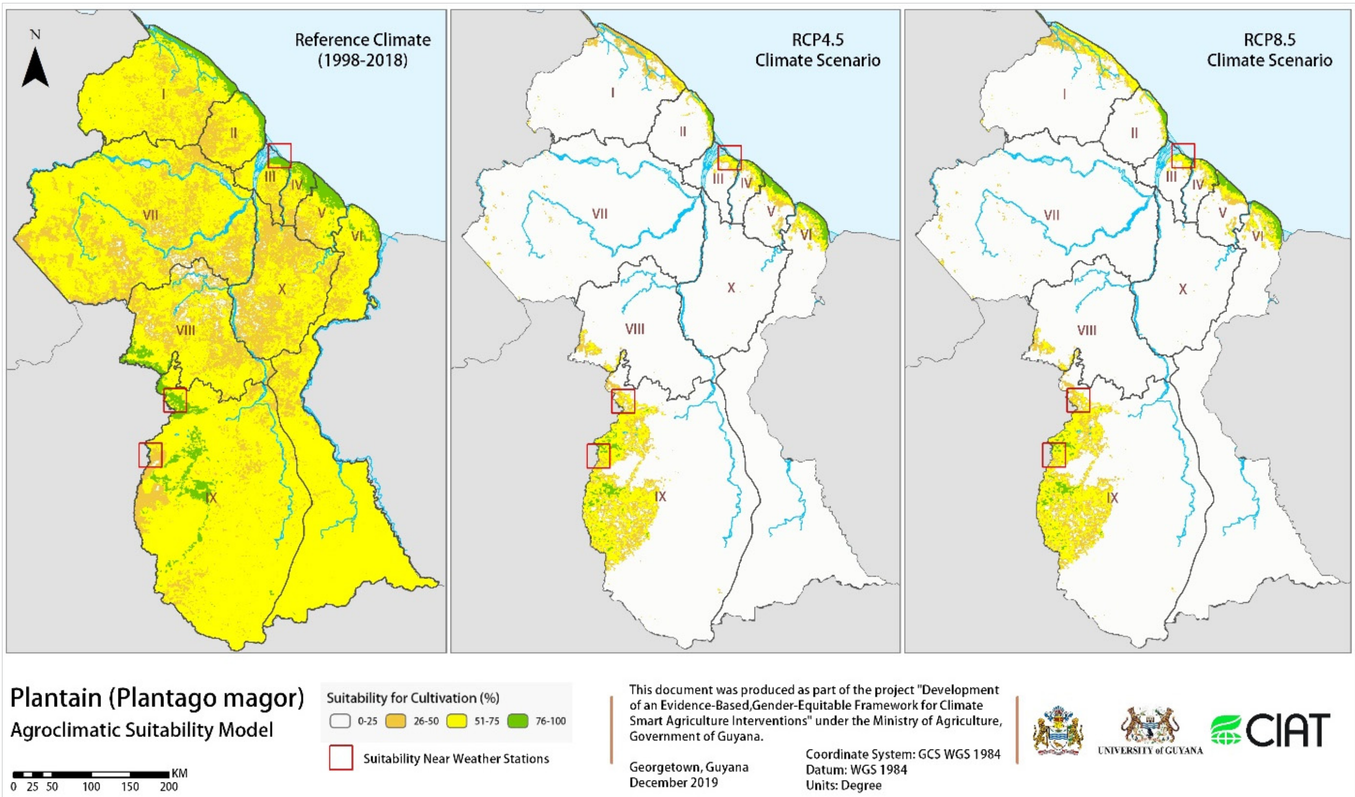

Figure 9 Spatial Suitability for Plantain: Reference (left) and Future Climates.

3.2.1. Spatial Modeling Trends

Reference Climate

Spatial modeling to derive cultivation suitability for the plantain crop under current climatic conditions returned a positive overall trend. Areas of high suitability exist along the coasts of Regions I to V, with some pockets along the Corentyne coast of Region VI. Lower Region VIII and sections of the Rupununi are also highlighted as highly suitable areas for this crop. These zones are characterized by sandy loam and silty clay loam soils rich in organic matter that supports the crop's development stages. Overall, most Regions experience favorable climate and soil pH that support greater scales of plantain cultivation.

Only some areas were returned as unsuitable for plantain cultivation: a few places near the Potaro River system in Region VIII and southwest areas of Region X. Densely forested areas in central Guyana, where logging and mining activities dominate, are generally returned as areas with relatively low and variable suitability. Other notable areas that follow this trend include South Central Rupununi areas near the Brazil border, lower areas of Region II, and the upper Mazaruni River's highlands. These areas comprise denser, poorly drained soils that could stymie root development (NAREI, n.d.-a).

Future Climate

In projecting geographic suitability for plantain in the future climate, significant differences arise against the reference climate period. Most notable is that both future scenarios returned large swaths across the country where climate conditions will no longer be suitable for plantain cultivation. Administrative Regions VII, VIII, and X that form central Guyana are projected to have low suitability. This crop requires optimal temperature and rainfall ranges of 18-32 °C and 1400-2000 mm, respectively. Climate change is likely to be problematic for this crop in areas where temperatures will increase, and precipitation will decrease.

In future climates, areas of marginal to high suitability become concentrated along the coastal plain's length, with the highest suitability areas expected at Regions II, V, and VI. This differs from current suitability trends because although the coastal strip will remain viable for plantain cultivation, a changing climate will mean fewer areas may be suitable for the crop in the future, which may negatively impact national yield. There is a notable decrease in suitable coastal areas from high to moderate suitability in all coastal regions, particularly in Regions I through IV. Although coastal Region VI displays less geographic area, its coastal zone is expected to experience a shift to high suitability in both RCP scenarios, compared with moderate to high suitability under near-current conditions. The spatial extent suitable for plantain cultivation along the coast is similar in both RCP4.5 and 8.5 scenarios.

At the Rupununi Savannahs, the RCP scenarios modeled similar suitability extents. Nevertheless, suitability types are expected to be more variable when compared with the reference climate. Future climate will comprise more marginal suitability (0-50%). In contrast, it is characterized mainly as moderate for plantain cultivation under the reference climate conditions. This is because the climate is expected to intensify in the future, bringing more extended drought periods and flooding that could interrupt the crop's development cycle. The Pakaraimas also follows the trends described here.

3.2.2. Crop Modeling Trends

Plantain production approximated 12 tons per hectare during the period 1998-2018 for Region III locations, but highly variable results between 0-8 tons per acre for Region IX. Overall, future simulations indicate that coastal Region III is more likely to have consistent and improved plantain yields in both rainfed and irrigated conditions, whereas Region IX should return low yields.

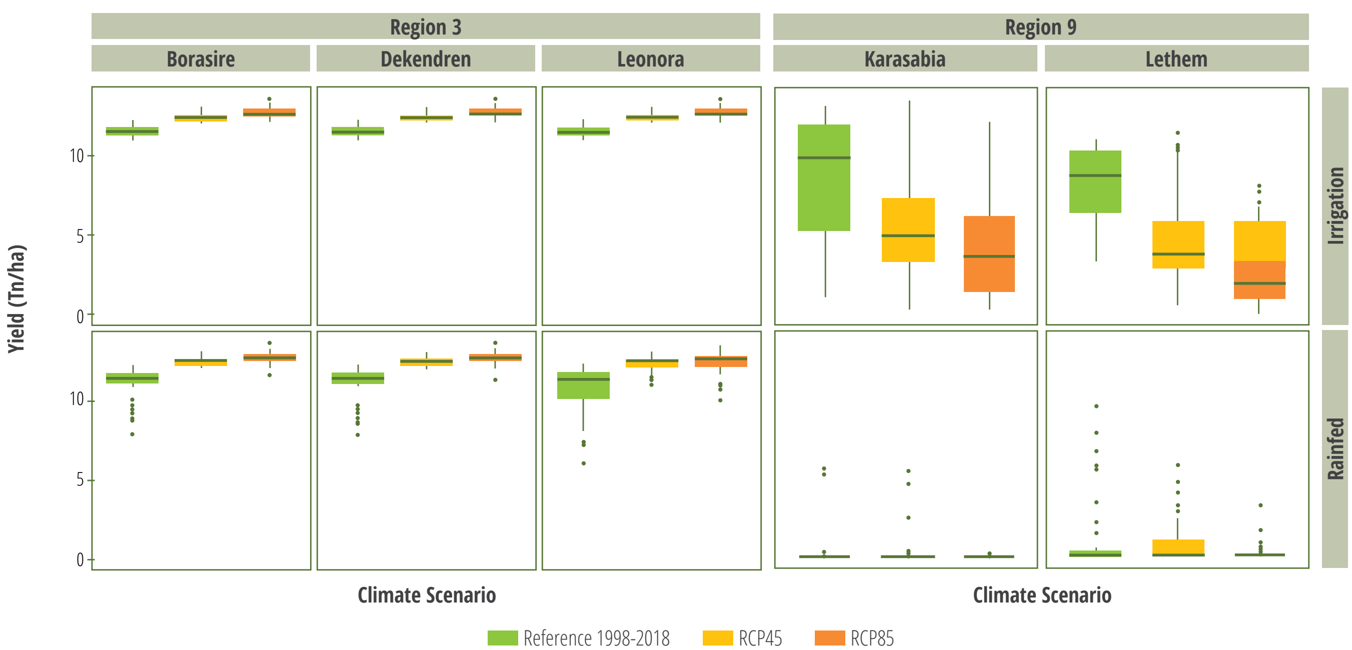

Figure 10 Yield Projections for Plantain at Region III (left) and Region IX (right).

Region III Model Results

For the 1998-2018 reference period, Boerasirie, De Kinderen, and Leonora returned averages of 12 tons per hectare in both irrigated and rainfed conditions. Future climate scenarios RCP4.5 and RCP8.5 averaged 13.5 tons per hectare in both irrigated and rainfed conditions. AquaCrop projects an increase of yields in both future climate scenarios above the 1998-2018 reference period for this Region. The RCP8.5 scenario consistently returned the highest yields for each location in all irrigated conditions.

Spatial modeling indicates that climate change will alter the Region's suitable areas for cultivation by limiting suitability to a 15km strip along the coast. Suitability levels transition inland from moderate to marginal suitability. Against these results, it would appear that while there is expected to be less productive land for plantain cropping, higher yields are expected in the areas which retain productivity.

Region IX Model Results

Region IX yields for the 1998-2018 reference period, and both future climate scenarios were almost non-existent under rainfed conditions. For Karasabai and Lethem in Region IX, rainfed cultivation returned low mean yields of 0 tons per hectare. The two future scenarios average 4.5 tons per hectare at Karasabai and 2.5 tons per hectare at Lethem, severely lower than yields indicated for the reference climate. Under irrigated conditions, the reference period averaged 9 tons per acre. However, future estimated yields of 2-5 tons per hectare were significantly lower than the present-day model average. In summary, even under irrigated conditions, future scenarios are not expected to be promising at Region IX for the plantain crop with current practices and technologies.

The crop modeling results correspond with the spatial modeling results for Region IX, where a changing climate is expected to strongly reduce the Region's productive area for the plantain crop. For the two locations studied in AquaCrop, agro-climatic suitability decreases by one class for each: from moderate to marginal at Lethem and high to moderate at Karasabai. In summary, both suitable areas and yields for plantain cultivation are expected to shrink in Region IX under future climate conditions.

3.2.3. Summary

Plantain is a sturdy sucker crop that is widely grown across Guyana. It is typically produced for subsistence and cash cropping on the lower reaches of rivers with lighter soils in rural areas. It is cultivated at larger production scales on the coastal plain, adapted to better-drained soils (NAREI, n.d.-a). Region III is a significant plantain producing area in Guyana that has historically been important to the domestic and export markets. In future projections through crop and spatial modeling, the Region is expected to maintain or increase current productivity with successful disease management. More consistent returns are forecast under irrigated conditions.

Plantain growers have struggled with disease management for the control of Black Sigatoka, which is recorded to have affected farms in most administrative regions in Guyana. Region III farming communities on the East Bank of the Essequibo River, such as Hubu, Parika, Salem, Larimakabra, and Tuschen, experienced significant devastation, with plantain farmers reporting as much as 90 acres of plantain crops lost to the disease and lower harvest weights. Black Sigatoka infestations completely halted plantain exports in the past ("Guyana's plantain exports fell," 2013). NAREI intervened to support farmers through intensive training in disease management to counter Black Sigatoka effects and improve yields ("Plans afoot to tackle," 2017). Essequibo Island farms in Region III at places like Wakenaam and Hamburg reportedly benefited from closer monitoring and management interventions by NAREI.

Of the ten administrative regions, larger-scale plantain cultivation is uncommon in Region IX due to unfavorable climate and soils that limit the plant's life cycle. Expanded cultivation of this crop in Region IX would require close irrigation and fertilization to be successful. Even so, forecasted scenarios through crop and spatial modeling are unfavorable to plantain in this Region, as suitable areas and estimated yields are projected to contract under future climate conditions.

3.3. Pineapple Models

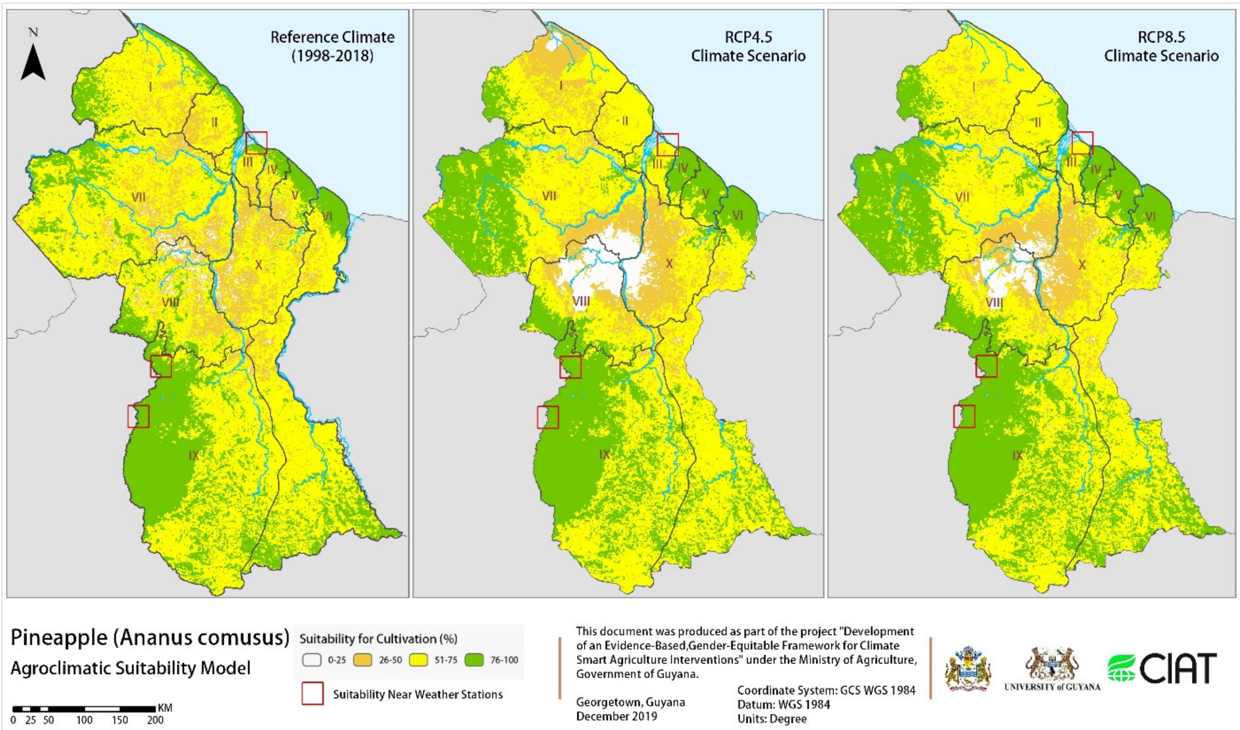

Figure 11 Spatial Suitability for Pineapple: Reference (left) and Future Climates.

3.3.1. Spatial Modeling Trends

Reference Climate

Spatial modeling for pineapple cultivation under reference climate conditions indicates mostly favorable trends across Guyana. The coastal strip and Rupununi Savannahs were returned as high suitability (75-100%) areas for this crop's successful growth. Most other areas of the country are denoted as moderate suitability (51-75%).

Pockets of central Guyana near the town of Mahdia at Region VIII were highlighted as areas with low suitability for pineapple cultivation due to unfavorable climate and soil characteristics. Marginal suitability areas are seen throughout Region X, south of the Mazaruni River, and region II areas. Although large areas of the country are indicated as favorable for pineapple farming, factors such as elevation and soil type could alter the results. Many areas indicated as moderately highly suitable are presently forested or focused on extractive activities such as logging and mining.

Future Climate

Suitability for pineapple farming in future climate exposed some notable differences compared against suitability patterns in the reference period climate.

In both RCP4.5 and RCP8.5 scenarios, these patterns have shifted mainly in the country's upper half. High suitability areas are expected to contract from the full coastal strip in near-current climate to cover most Regions IV and V, and coastal Region VI. Projected temperature and precipitation at the westernmost sections of Guyana (at Regions I and VII) should also favor pineapple cultivation. Areas near the Cuyuni-Mazaruni-Essequibo River confluence shift one level to a highly suitable zone for this crop.

However, the area near Mahdia, under the reference climate, is denoted as low suitability area. The crop is expected to expand further, extending to cover much of Region VIII, along the Demerara River in Region X, and the Essequibo River's middle course. This pattern is evident in both future climate scenarios but is most pronounced in RCP4.5. Therefore subsistence level pineapple farming at indigenous communities like Malali, Muritaro, and Chenapau could be negatively affected if the forecasted climates are realized. As for the remainder of the lower half of the country, future suitability patterns remain fundamentally similar to spatial modeling under present-day conditions. Pineapple cultivation at Region IX and inland Region VI is therefore expected to succeed in these areas despite climate change projections.

3.3.2 Crop Modeling Trends

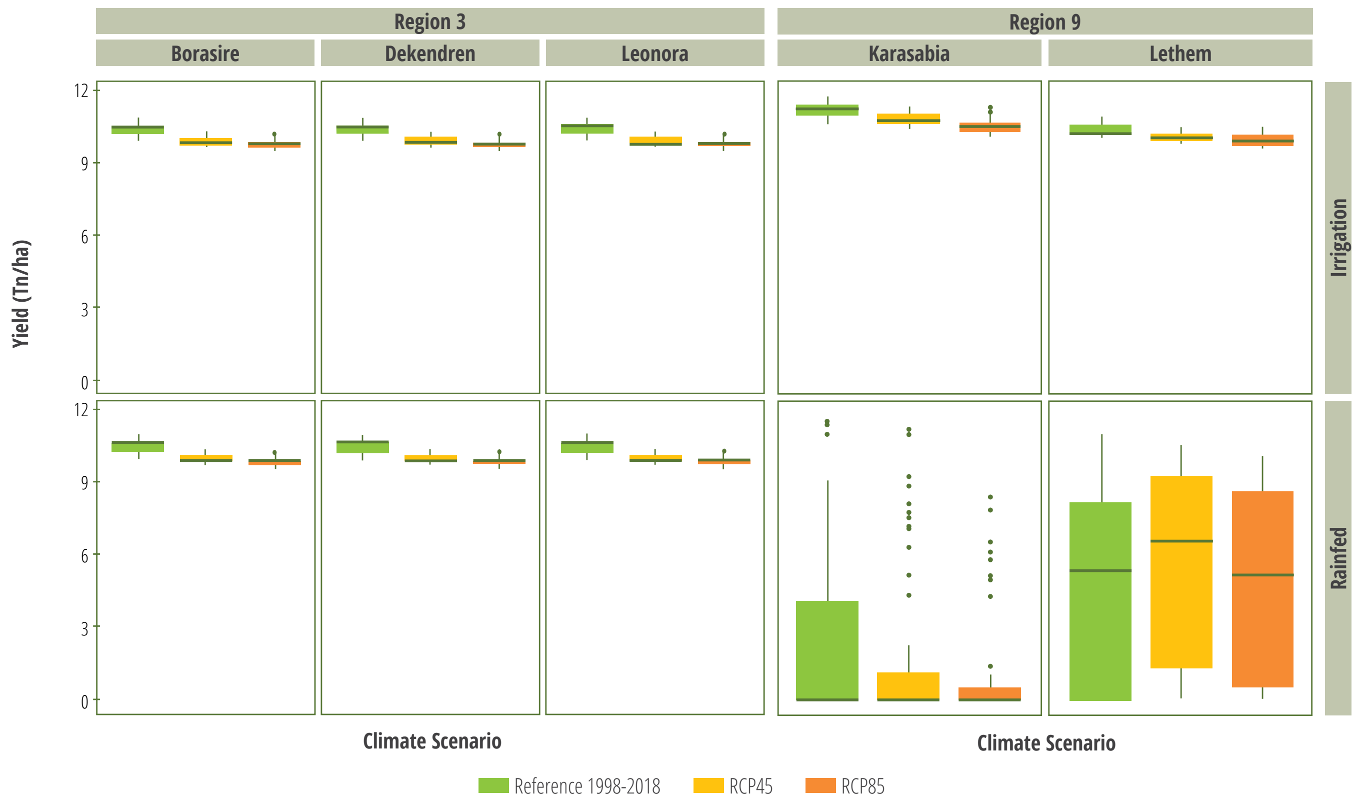

Figure 12 Yield Projections for Pineapple at Region III (left) and Region IX (right).

Region III Model Results

AquaCrop simulations for pineapple production at Region III yielded approximately 11 tons per hectare during 1998-2018 at Boerasire, De Kinderen, and Leonora. Crop modeling returned decreasing yields in the future climate scenarios, averaging 10 tons per hectare. This trend is projected to occur under both rainfed and irrigated conditions at the three locations, with the lowest yields expected under the RCP8.5 climate. These results are consistent against spatial modeling results for Region III under rainfed conditions. Decreased yields from rainfed pineapple farming are implied in the Region's drop from high to moderate (50-75%) suitability under future climate scenarios.

Region IX Model Results

At Karasabai in Region IX, all scenarios returned dismally low yields of 0 to 2 tons per hectare under rainfed conditions. However, this trend considerably improves under irrigated conditions. Present-day irrigated pineapple yields indicated at Karasabai average 11 tons per acre. Under future climate scenarios, the mean yield projections decrease slightly to 10.5 t/ha and 10 t/ha at RCP4.5 and RCP8.5, respectively. Pineapple yields are higher at Lethem with mean yields of 8 tons per hectare under rainfed simulations. RCP4.5 climate is expected to return the most successful yields. However, rainfed crop simulations return high variability ranging from 0 - 9.5 tons per hectare. These weak means suggest that future climate at Lethem may result in uncertain pineapple crop yields at that location.

Like Karasabai, crop model simulations for Lethem under irrigated conditions are more robust and constant. Yields average 10 to 11 tons per hectare for the three scenarios, with the most robust returns at the reference period/current conditions. The lowest yields (10 t/ha) are probable under the RCP8.5 climate. The spatial modeling results indicate mainly suitable areas across the Region under rainfed conditions. The crop model results suggest that yields at the two locations understudy will either be low or highly variable without irrigation methods at pineapple farms. Overall, future climate scenarios can support irrigation-enabled pineapple cropping at Region IX.

3.3.3 Summary

Pineapples thrive in temperatures ranging from 15.5 – 32.5 degrees Celcius and rainfall ranges of 1000-1500 millimeters and up to 2500 millimeters (NAREI, n.d.-b). It persists on well-drained sandy loam soils with a pH range of 4.5-5.5. However, commercial cultivation in Guyana occurs mainly on riverain silt loams, clay loams, and pegasse soils on the flatlands where drainage systems support crop development (NAREI, n.d.-b). Pineapples are widely grown in Regions II, III, IV, and VI ("Our pineapple industry," 2012; Velloza, 1993), with Region III dominating the export market. Pineapple is noted to have contributed 7.0 percent to increased fruit production in the first half of 2018 (Ministry of Finance, 2018). Yield for this crop at Regions III and IV were reported to average 15 t/ha ("Our pineapple industry," 2012). This figure is somewhat higher than that modeled in Aquacrop for the 1998-2018 reference period, which averaged about 11 t/ha at the Region III locations under both rainfed and irrigated conditions. Those growing areas correspond with spatial modeling results, accounting only for suitability under rainfed conditions.

Future climate is expected to reduce suitability for pineapple at Regions II and III slightly but is expected to benefit farmers at Regions VI, V, and VI. However, introducing new agricultural technologies and practices could help sustain production by pineapple farmers at places like Mainstay/Whyaka in Region II and East Bank Essequibo. Pineapple cultivation is not widespread at Region IX despite adequate suitability levels derived from spatial modeling in current and future climate scenarios. AquaCrop modeling better catered for this CAM crop's broader phenological characteristics and indicates that yields will be either low or highly variable at Lethem and Karasabai, respectively, under rainfed conditions. However, irrigation practices are projected to support the crop's development to provide adequate commercial yields comparable to Region III.

3.4. Cassava Models

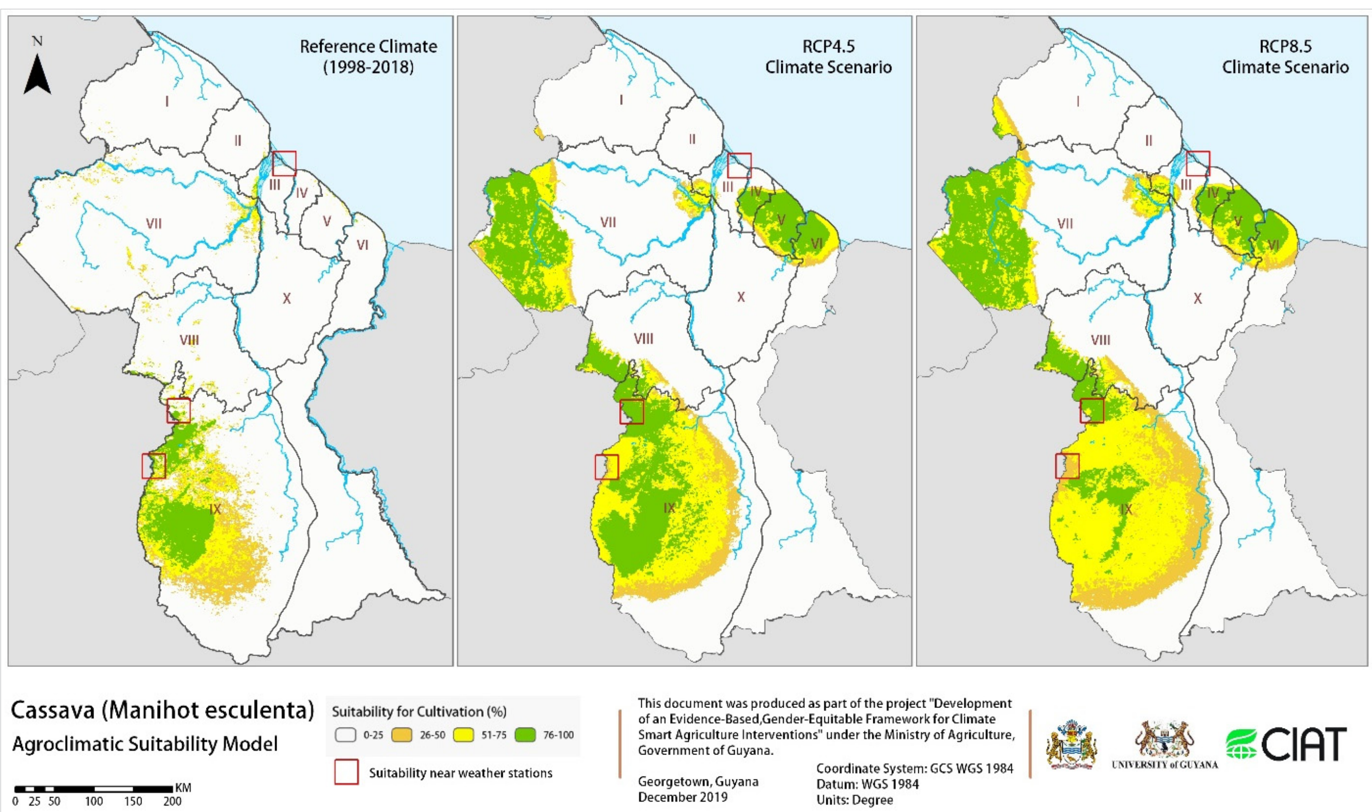

Figure 13 Spatial Suitability for Cassava: Reference (left) and Future Climates.

3.4.1. Spatial Modeling Trends

Reference Climate

Spatial modeling based on climate data for the 1998-2018 reference period amplifies the Rupununi Savannah's ecoregion of Region IX as favorable for cassava cropping. Most areas of North, Central, and South Rupununi show high to moderate suitability, and some upper areas of the Deep South sub-district are indicated as moderate suitability. Small pockets of Regions VII and VIII are returned as moderate suitability (50-75%), with the most extensive zone near the confluence of the Cuyuni, Mazaruni, and Essequibo Rivers in the vicinity of Bartica township. Small areas on the coast are also highlighted as suitable areas for cassava. Much of the remainder of the country is indicated as low suitability areas under the historical rainfed conditions.

Future Climate

Projections for cassava cultivation based on future climate scenarios forecast new suitability areas from those seen in present-day conditions. Both RCP scenarios estimate the following changes:

- Western areas of Region VII in upper Mazaruni and southwestern areas of Region VIII should experience favorable precipitation and temperatures, switching it from a low to high suitability area for the cassava crop;
- Regions IV, V, and coastal areas of VI should shift to high suitability. Region IV's suitability extent is focused more on areas of the old coastal plain;
- The moderate suitability zone highlighted near the Cuyuni-Mazaruni-Essequibo confluence is projected to expand into upper Region III radially and VII, with RCP8.5 returning more successful projections; and
- The suitability extent at Region IX should increase. More high suitability areas are projected across the Region under RCP4.5, whereas RCP8.5 assigned more conservative suitability projections but with slightly wider spatial extents.

Under future climate, the drought-tolerant cassava crop is expected to succeed in more biogeographic areas across Guyana. Coastal communities and Amerindian villages in the interior should have prospects for expansion and intensification of cultivation efforts in the listed areas.

3.4.2 Crop Modeling Trends

Through AquaCrop modeling, cassava production was shown to yield approximately 17 tons per hectare during 1998-2018 at Region III. It returned higher yields in both future climate scenarios above the reference period. For Region IX, this trend only occurred under irrigated conditions. Overall, the results indicate higher average yields at Region III locations (about 19 tons per hectare in both rainfed and irrigated conditions) than Region IX, which averaged 12-15 tons per hectare under irrigated conditions only.

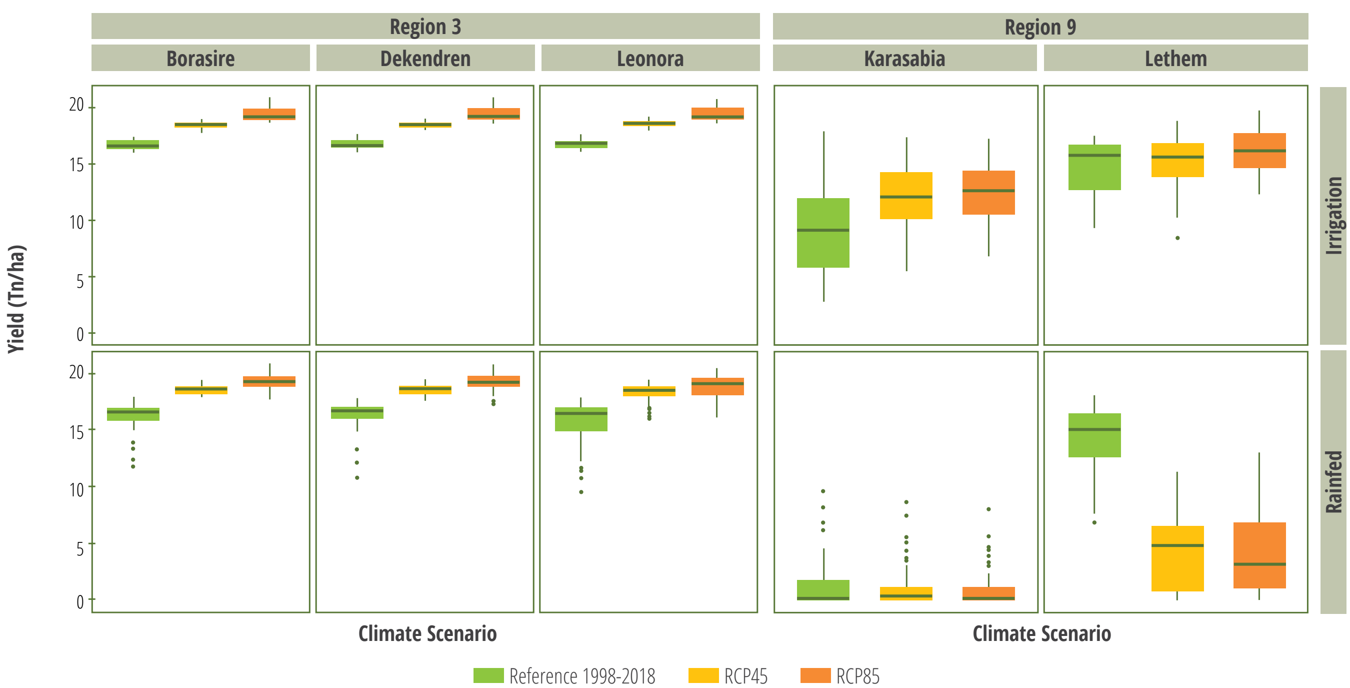

Figure 14 Yield Projections for Cassava at Region III (left) and Region IX (right).

Region III Model Results

The three localities in Essequibo Islands-West Demerara (Region 3) – Boerasirie, De Kinderen, and Leonora all returned yields were averaging 16 tons per hectare for the 1998-2018 reference period. Future climate scenarios RCP4.5 and RCP8.5 simulate higher yields for cassava, averaging 17-18 tons per hectare in irrigated and rainfed conditions. The RCP8.5 scenario, which considers increasing greenhouse emissions over time, returned the highest yields at all locations and conditions. Spatial suitability modeling implied that much of Region III had low suitability climate conditions for growing cassava, with the only change in future scenarios noted in the upper estuary areas of the Region.

Region IX Model Results

The spatial modeling results for Region IX suggested high suitability for cassava cropping under the reference climate at Lethem, with suitability dropping by one level after climate change. Crop modeling supported those results as Lethem returned good yields (15 tons/hectare) under rainfed conditions but weaker mean yields (3-4 tons per hectare with high variability) in future climate scenarios. At Karasabai, spatial modeling indicates low suitability for the cassava crop under reference climate, aligning with the AquaCrop findings (0-3 t/ha). However, a dramatic shift to high suitability is expected at the village in the future; this, despite low yields maintained in the crop model under rainfed conditions. At both locations, irrigated conditions appear to provide the most favorable yields. Under irrigation in the future climate, Karasabai is predicted to yield about 12 tons per hectare.

In comparison, Lethem is expected to yield 16 tons per hectare. Future climate simulations predicted higher mean yields at both locations above the 1998-2018 reference period, with the RCP8.5 condition returning the most robust yield results. Overall, among all locations, climates, and conditions studied for the Region, irrigated cassava farming at Lethem is expected to be most successful in the future in the RCP8.5 climate, with expected yields at 16 t/ha.

3.4.3 Summary

Cassava is an essential staple for local indigenous populations and the most widely grown root crop in Guyana. This perennial root crop is adapted to deep, well-drained soils with an optimum pH between 5.5 and 6.5 (FAO, n.d.; NAREI, n.d.-c), and thrives in zones with temperatures of 25-32 degrees Celsius and annual precipitation of 1000-1500mm. A drought-resistant crop has been cultivated at Regions III, IV, and IX at commercial scales and in Amerindian settlements throughout Guyana for subsistence purposes. Bitter cassava contributed to modest increases in the root crops sub-sector (Ministry of Finance, 2019). However, production quantities have considerably dropped in the past decade as farmers deal with weather events related to climate change. Hinterland farmers have reportedly struggled with low yields from crop pests and prolonged drought events ("Region Nine farmers gifted," 2019).

Crop modeling has indicated that cassava grown in Region III is expected to achieve high yields in the future under both irrigation conditions. At Region IX, successful cassava production will occur under irrigated conditions and generally improve with climate change as annual precipitation levels are projected to drop. Future climate characteristics at both Regions are forecast to favor the cultivation of the cassava crop. RCP4.5 and RCP8.5 scenarios further indicate new areas projected to be highly suitable for cassava cultivation: Region VII highlands, where Upper Mazaruni indigenous communities such as Kamarang, Kako, and Paruima stand to benefit; and Regions IV through VI, where the expansion of cassava production can occur at those coastal areas.

Food security is threatened by climate change and is particularly problematic for the cassava crop. It is the main staple of many hinterland communities. Efforts have been made to intensify Guyana production through farmers' training of improved agronomic practices and mechanization techniques. In 2019 Region IX farmers were gifted a new, fast-growing variety of cassava sourced from the Brazilian Agricultural Research Corporation, Embrapa ("Region Nine farmers gifted," 2019). The cultivar is expected to reach maturity two to three times sooner than traditional varieties. Such initiatives are intended to strengthen Guyana's capacities for food security. Paired with the generally favorable results derived through crop and spatial modeling, yields can improve over time once climate-smart interventions are successfully adopted. More cultivable land becomes available to farmers. Robust irrigation techniques and pest control to manage caterpillar infestations will be vital to improving Guyana's cassava crop yields.

3.5. Sweet Potato Models

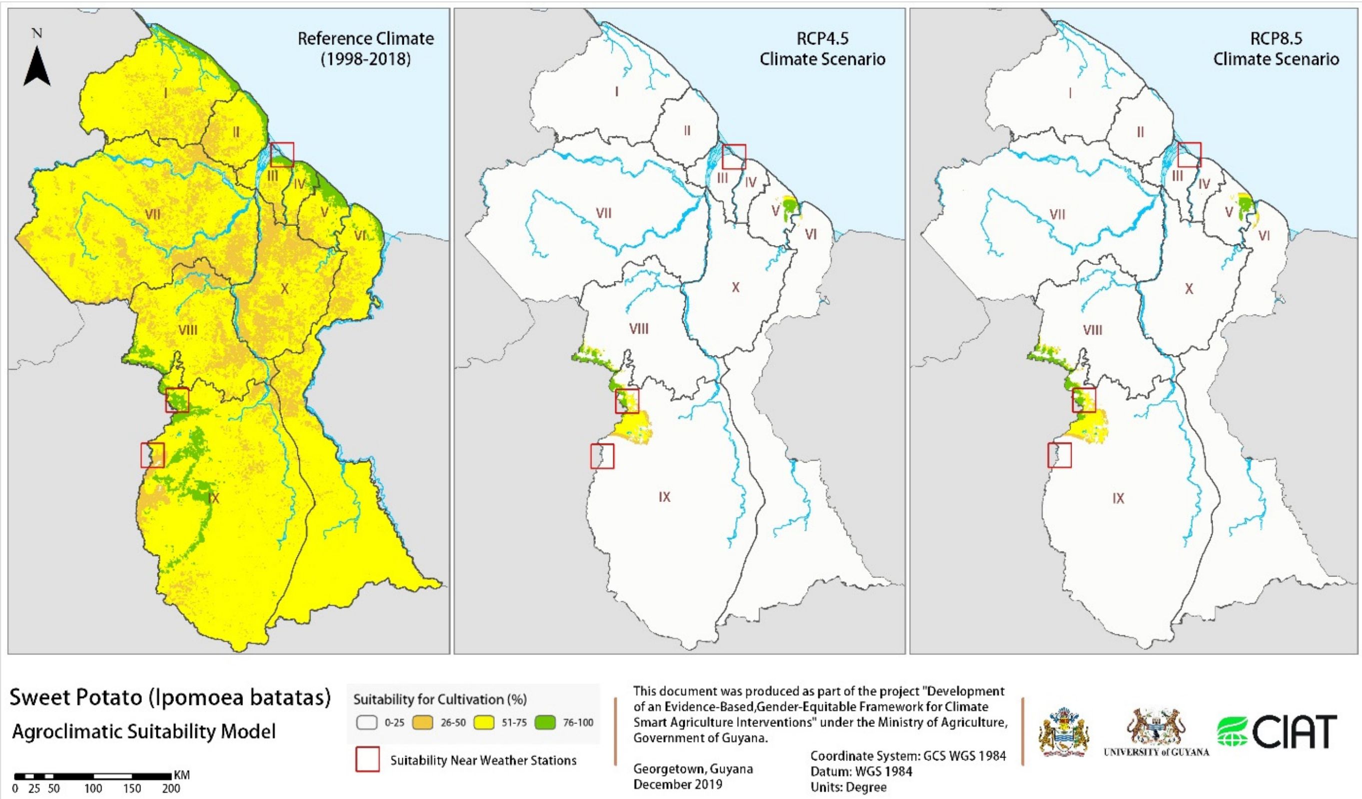

Figure 15 Spatial Suitability for Sweet Potato: Reference (left) and Future Climates.

3.5.1. Spatial Modeling Trends

Reference Climate

Current trends for the sweet potato crop's spatial suitability are indicated as generally positive across all ecological zones of Guyana. High suitability areas were derived along the narrow coastal strip from Regions I through VI and in some savannah areas of Region IX. Other administrative regions are primarily indicated as having suitable annual rainfall (800-1000mm), temperatures (24-35 degrees Celsius), and soil acidity (5.6-6.6 pH) to support the crop. Some marginal suitability (25-50%) for sweet potato cultivation is seen near central Guyana and interior areas of Regions I and II. These results mirror current cultivation trends, as sweet potato is mainly cultivated at Regions II through VI and Region IX.

Future Climate

Future suitability modeling for sweet potato derived highly contrasting results against the reference climate simulation. Most areas of the country were modeled as low suitability (0-25%). The North Rupununi Savannahs, Berbice River, and Canje Rivers are predicted to maintain moderate to high suitability for sweet potato farming under rainfed conditions. Both RCP scenarios returned uniform results. They appear to respond heavily to rising estimates of total annual precipitation across Guyana. As sweet potato generally requires less rainfall for crop growth, this may be problematic for its cultivation in future scenarios.

3.5.2. Crop Modeling Trends

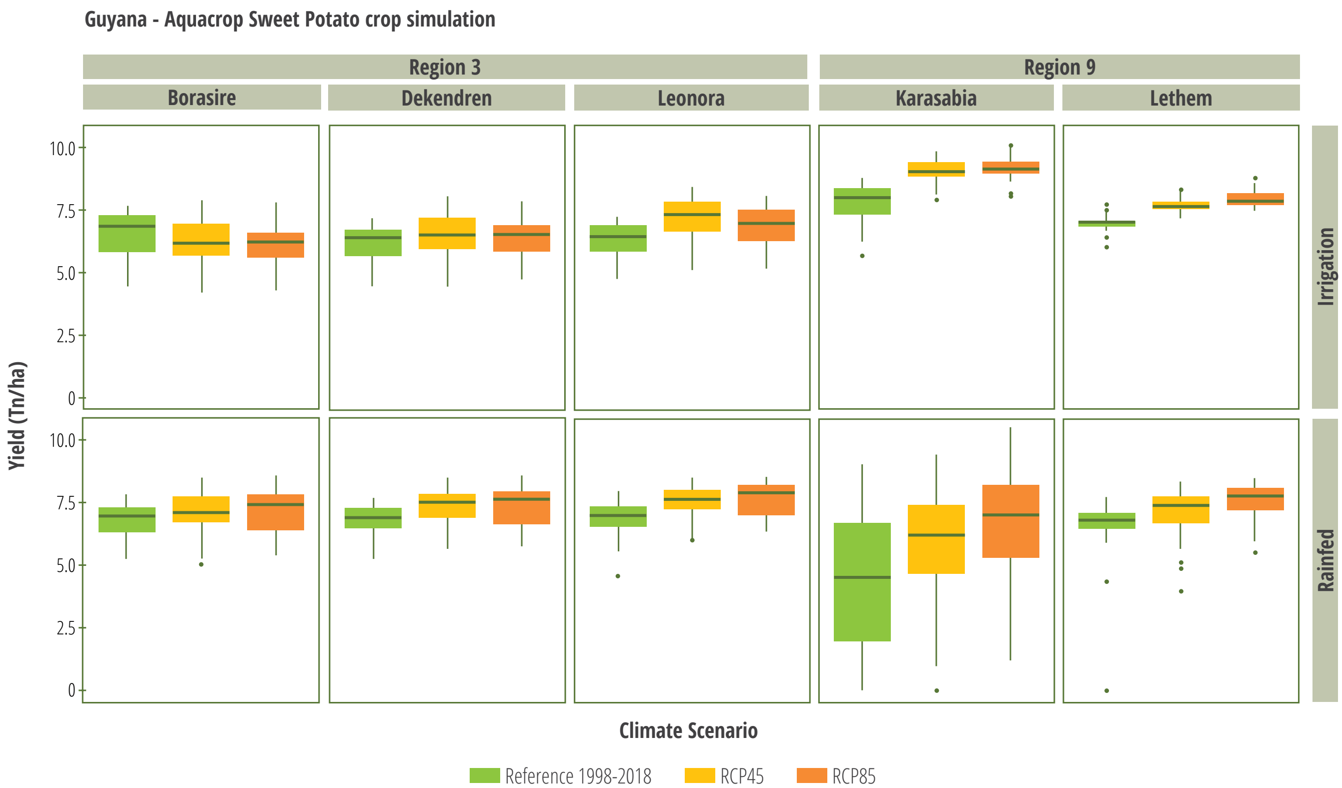

Figure 16 Yield Projections for Sweet Potato at Region III (left) and Region IX (right).

Region III Model Results

Sweet potato production simulated in AquaCrop yielded approximately 6 tons per hectare during the 1998-2018 reference period for the Region III locations – Boerasirie, De Kinderen, and Leonora; and returned varying yields in future climate scenarios. Boerasirie was shown to have 7.5 tons yields per hectare under irrigated conditions but predicted lower yields averaging 6 tons for both future climate scenarios. Irrigated conditions for the future were otherwise comparable with the reference period for De Kinderen and Leonora. Among all the simulations, the RCP4.5 model was shown to produce the highest yield result at Leonora under irrigated conditions. At other locations, the RCP8.5 scenario returned the highest yields by about 1 ton. Overall, the mean predicted future yield was 7 tons per hectare. Rainfed conditions were projected to enable moderately higher yields (about 7.5 tons per hectare) at the three locations than the previous 1998-2018 reference period.

Region IX Model Results

Crop modeling at the Region IX locations generally returned higher and more consistent yields under irrigated conditions than rainfed conditions. All projections indicate improved yields under future climate scenarios, particularly under RCP8.5. Sweet potato yield simulations at Lethem were similar in both irrigation conditions: averaging 7 tons in the reference period climate, 7.5 tons in the RCP4.5 scenario, and 8 tons in the RCP8.5 scenario. However, more robust means were seen in the irrigated condition at Lethem.

At Karasabai, rainfed simulations for sweet potato derived the lowest mean yields and most significant variance. Reference period mean yields at 4.5 tons/ha saw an improvement to about six tons/ha in future climate scenarios. However, yield projections under irrigated conditions at Karasabai returned the highest yields simulated for the Region, with eight tons/ha and nine tons/ha averages projected under the reference period climate and RCP climates, respectively.

3.5.3 Summary

Sweet potato is the second most widely grown root crop in Guyana (Ministry of Agriculture, 2016a). It is valued as a drought-tolerant crop adapted to a variety of local soils. It persists in areas with annual rainfall ranges of 800-1000 mm with soil pH preferred at 5.6-6.6 (NAREI, n.d.-d). High production areas for this root crop occurs mainly in Regions III, IV, and IX. Other notable growing areas include Regions II, V, and VI (NAREI, n.d.-d).

Sweet potato is an essential crop to food and nutrition security but is considered underutilized, mainly globally (Motsa et al., 2015). The Guyana Ministry of Agriculture has focused on this crop as part of the Agricultural Diversification Project, which aims to promote the cultivation of non-traditional crops (Ministry of Agriculture, 2016b). NAREI has performed trials at Mon Repos and Parika to determine the effects of sprinkler irrigation on sweet potato yield. A recent collaborative research effort is expected to increase crop production through seed quality studies.

Crop modeling generally indicates that yields will hold steady in Region III in future climate scenarios. Simultaneously, Region IX can generally expect higher yields than those under the reference climate period. However, spatial suitability results imply that RCP-simulated increases in annual precipitation may no longer enable such vast swaths of the country to support sweet potato farming, given that the crop thrives in areas with lower rainfall ranges. Nonetheless, adequate irrigation, fertilization, weed control, and integrated pest management against the sweet potato weevil and other pests can supply a successful harvest. Farmers stand to benefit once they can engage in farm management practices that ensure the crop's success against adverse effects brought on by waterlogging and pests.

3.6. Peanut Models

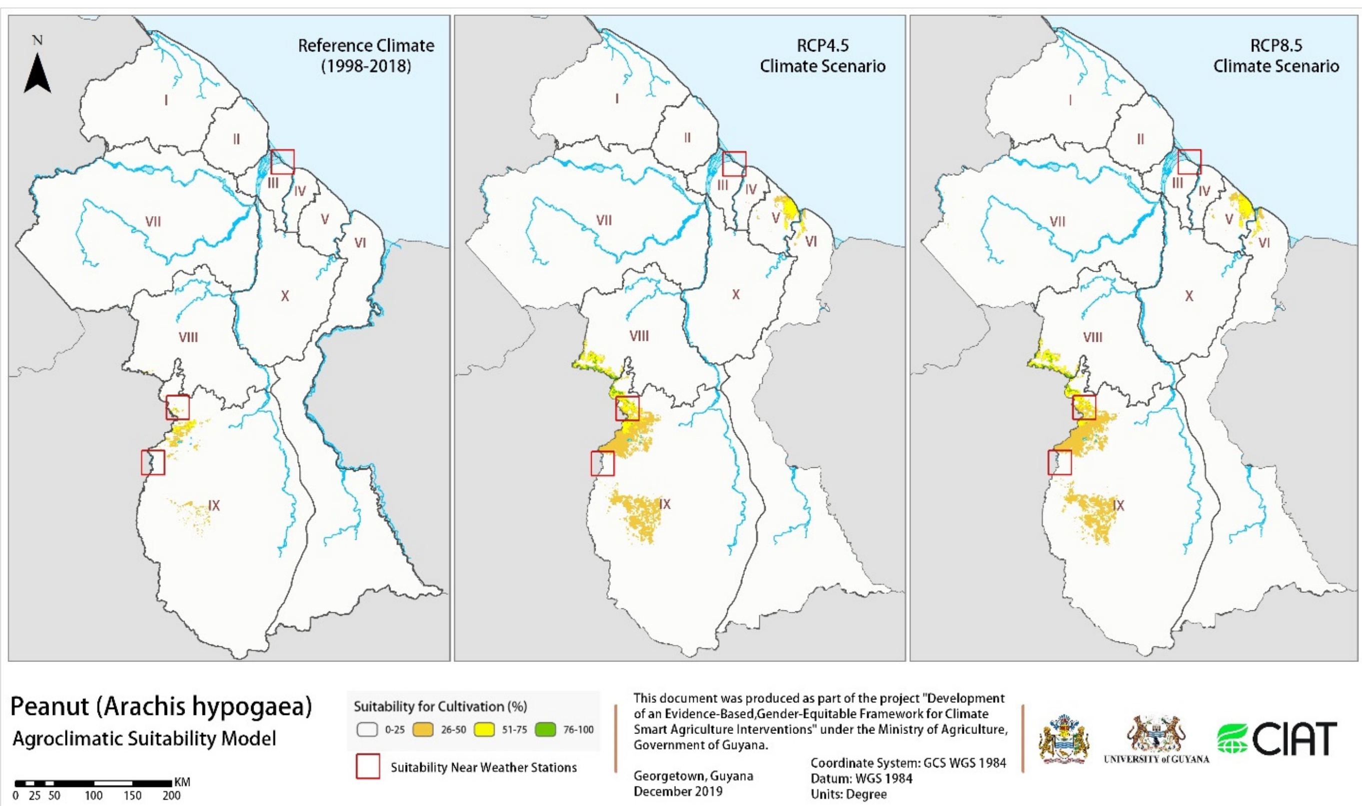

Figure 17 Spatial Suitability for Peanut: Reference (left) and Future Climates.

3.6.1 Spatial Modeling Trends

Reference Climate

Spatial modeling to derive suitable areas for peanut cultivation indicates that most administrative regions generally do not obtain temperatures and rainfall that favor this crop. Sections of the North and South Rupununi Savannahs were returned as having climate and soil characteristics of marginal to moderate (25-75%) suitability for peanut farming, effectively reflecting the present-day farming trends for this crop. The optimal climate ranges for peanuts to grow are mean temperatures of 22-27 degrees Celsius and 750-1250 mm total annual rainfall (NAREI, n.d.-e). Peanut has a low tolerance for saline soils and experiences optimal growth in looser, sandy, and slightly acidic soils ranging from 6.0-6.5 Ph. Although peanut farming is undertaken at small scales in other areas of Guyana (e.g., Region II and VI), such locations are indicated as low suitability areas based on the historical temperature, rainfall, and soil acidity trends.

Future Climate

The spatial suitability modeling for peanut simulated increases in suitable areas at locations in the Rupununi Savannahs. This is especially evident along with border areas north of Lethem, Karasabai, and Orinduik at Region VIII. Spatial suitability is also indicated in South Rupununi villages such as Sand Creek, Maruranau, Aishalton, and Achiwuib. For coastal areas, Regions V and VI emerge as predominantly moderate suitability (50-75%) for peanut farming – especially along the Berbice River. RCP4.5 and RCP8.5 returned similar results. The increase in suitable areas projected for peanut cultivation is the model's response to RCP reductions in total precipitation at the Savannahs, Region V, and Region VI areas. Peanut will thrive in areas with lower rainfall amounts.

3.6.2 Crop Modeling Trends

AquaCrop was not applied in full for modeling peanut. Preliminary modeling indicated that Region III locations yielded approximately 11 tons per hectare under the reference period climate. In comparison, Region IX locations derived higher mean yields at about 13 tons per hectare. Both Regions were predicted to have higher yields under future climate: Region III showing increases by about 2 tons, and Region IX forecasting increases by 1 ton.

3.6.3 Summary

Peanut farming in Guyana is concentrated mainly in the Rupununi Savannahs. It is the primary cash crop of many Region IX farmers. It is a historically significant feature of the rural economy. Peanut production declined in recent decades as farmers transitioned to other cash crops after being confronted with a challenging economy featuring reduced prices, lower local consumption, and the threat of low-priced peanut imports (Haire, 2007). Peanuts can thrive in other areas of the country, and cultivation at other places such as the Linden-Soesdyke highway is generally undertaken at small scales. New farms have emerged for this crop in coastal areas such as St. Deny's in Region II (NAREI, 2016) and Orealla in Region VI. These locations were modeled as unfavorable for growing peanuts due to historically higher rainfall amounts. However, longer dry seasons would enable the crop in coastal areas with low saline profiles. Increases in suitable areas at Regions V and VI and the Rupununi Savannahs should bolster future peanut productivity if more farmers use the crop or expand existing farms. The legume is not typically part of the cash crop profile by coastal farmers. However, enterprising farmers are exploring peanut processing to produce peanut butter, punch, and nut bar products. Farmers and community groups interested in pursuing this crop have benefitted from training sessions by NAREI to help them improve yield and guard against crop pests and diseases ("Orealla farmers receive training," 2017). Drivers of farmers' interests in this crop's future focus on boosting yield through new varieties and advanced cropping systems, along with value-added processing (Cho et al., 2016; NAREI, 2016). Overall, the leguminous crop is expected to thrive in future climate scenarios at existing Savannah areas and coastal areas with slightly acidic soils.

3.7. Coconut Models

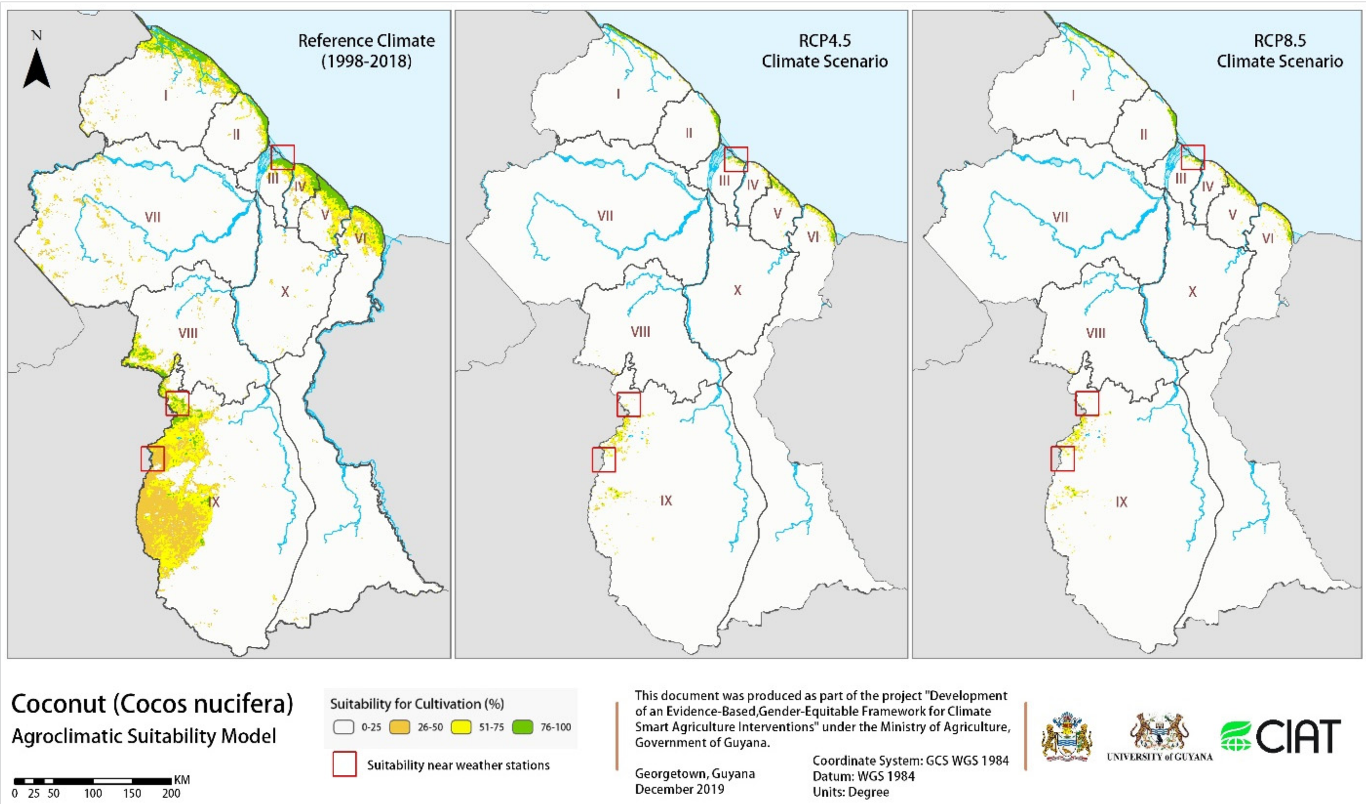

Figure 18 Spatial Suitability for Coconut: Reference (left) and Future Climates.

3.7.1 Spatial Modeling Trends

Reference Climate

Spatial modeling results imply that under current climate and soil acidity conditions, the most suitable areas for coconut cultivation mainly occur along the young coastal plain, capturing as much as 15 kilometers inland along the coastal regions. This is generally in keeping with the present coconut cultivation patterns, where extensive growing areas are found in administrative regions Pomeroon-Supenaam (Region II), Demerara-Mahaica (Region IV), and Mahaica-Berbice (Region V).

Areas of moderate suitability (50-75%) based on current agro-climatic conditions can potentially cause coconut cultivation with suitable drainage and fertilization. Such areas include coastal regions (notably Regions I, V, and VI), in the area of the white sand of the old coastal plain; and the Rupununi Savannahs – ranging along the pen plane from the South Pakaraimas to the South Central Rupununi sub-regions, and the foothills of the west Kanuku mountains.

The overall suitability trend for coconut cultivation under rainfed conditions is indicated as low suitability (0-25%) over the country's remaining areas. Regions VII, VIII, and X are noted as limited areas for coconut cultivation to thrive.

Future Climate

Spatial modeling to estimate suitable areas for coconut cultivation based on future climate scenarios RCP4.5 and RCP8.5 indicated a significant drop in suitable areas for this crop under rainfed conditions. This trend is seen across most countries, particularly in Regions I, II, and IV. Areas of moderate to high suitability become concentrated along a narrow strip at each coastal region.

Climate variability is generally projected to increase coconut productivity once irrigation and field management are made available in future climates (Kumar & Aggarwal, 2013). Data is not available for projected yields, but both models indicate reduced spatial extents in the target Regions. At the Essequibo Islands, East Bank Essequibo areas, and West Coast Demerara areas of Region III, these lands are expected to maintain suitability. At the Rupununi Savannahs, the spatial extent is projected to drop considerably to areas mainly north of Lethem. These forecasts are relatively parallel in both RCP climate scenarios.

3.7.2 Summary

Growth and Production

Commercial coconut plantations are usually located in hot and wet tropical climates. They require year-round warmth and moisture to grow well and fruit. Coconuts are widely cultivated at commercial levels in Guyana's coastal regions, with concentrations at Regions II, IV, V, and VI. Notable areas include the Pomeroon River, the Essequibo Coast, East Demerara, West Berbice, and the Corentyne Coast. Cultivated land by lead farmers ranges between 8-700 acres (Trotz, 2020). Coconut farming is a priority crop and ranks third in national acreage and exports (Ministry of Agriculture, 2013). However, its potential has been under-exploited (Homenauth, 2005).

	Year	Acreage (Acres)	Coconut (Dry)	Coconut (Water)	% Change - Coconut Dry
Production (mt)	2010	N/A	92,507	N/A	N/A
	2011	N/A	17,166	N/A	(81.44)
	2012	N/A	17,073	N/A	(0.54)
	2013	N/A	23,216	N/A	35.98
	2014	23,948	21,161	3,192	(-8.85)
	2015	24,820	20,104	4,159	(-4.99)
	2016	28,410	18,012	4,725	(-10.41)
	2017	28,410	15,786	14,570	(-12.36)
	2018	28,410	13,877	17,130	(12.09)

Table 4. Coconut production and acreage: 2010–2018.

The coconut palm thrives on sandy soils and is highly tolerant of salinity. It prefers abundant sunlight and regular rainfall (1500–2500 mm) throughout the year. Coconuts also need high humidity (at least 70–80%) for optimal growth. However, they prove quite adaptable and can be found in consistently warm and humid areas but have low annual precipitation. The palms also require no or little overhead canopy as direct sunlight must be maintained throughout the growth stages. Coconut plants growing on the coast sometimes exhibit sub-optimal growth. They are limited by hyper-saline conditions and thin, poorly developed soils. Yield is determined by the combination of genetic and environmental factors along with the level of management, soil conditions, and pests and diseases affecting coconut cultivation (Menon & Pandalai, 1958).

In Guyana, local growers typically apply cropping systems with two varieties of the tall cultivar and two varieties of the dwarf cultivar (Homenauth, 2016). Tall cultivars are the primary source of copra and coconut oil, while dwarf cultivars are grown for coconut water consumption. The 'Bastard Nut' variant is grown in the Pomeroon River area and is cultivated for both copra and sweet water. The coconut palm is subject to the various attack of pests and diseases such as the red palm mite (*Raoiella indica*), red palm weevil (*Rhynchophorus ferrugineus*), scale insects (*Coccoidea* sp.), whiteflies (*Aleyrodoidea* sp.), coconut rhinoceros beetle (*Oryctes rhinoceros*), coconut mealybug (*Nipaecoccus nipae*) and coconut red ring nematode (*Bursaphelenchus cocophilus*). These can cause palm loss, malformed nuts, reduce nut sizes, and stunt the overall growth of coconut trees.

The coconut industry has received much attention in recent years due to the growing market popularity of coconut water and coconut oil products. The Caribbean Agricultural Research and Development Institute (CARDI) and other institutions have undertaken the phased project: Coconut Industry Development for the Caribbean (Trotz, 2020). Guyana is one of nine participating Caribbean territories. Three pilot zones were identified: Regions II, IV/V, and X. Promotion of improved farming practices and extension services to increase integrated pest and disease management are among the objectives of the project. Following baseline survey, local coconut farmers' characterization, and training, an industry target of 100,000 acres of cultivation was set for 2026 and for the industry to contribute 6% to GDP (Trotz, 2020). Climate change and variability were areas of focus for the alliance project. It sought to introduce the climate-smart practice of intercropping coconut palms with cash and orchard crops to farmers as a technique for climate adaptation and risk mitigation.

Crop Modeling and Climate Change

Coconut farming is at risk of drought and other prolonged atmospheric events, despite the palm's tolerance for high temperatures. Coconut has a maturation period (from flowering to fruit ripening) of approximately 18 months, making it vulnerable to reduced yield caused by protracted weather events. Therefore, it is challenging to assess climate change impacts on this crop. Its growth stages last for multiple growing seasons. Perennial plantation crops that feature long periods of maturation cannot be modeled using herbaceous crop growth models like AquaCrop.

The unavailability of crop models capable of simulating perennial crops' yields under different climatic conditions and agronomic treatment regimens is a limitation for coconut producing countries. However, climate science and agricultural forecast models can help increase coconut plantations' resilience to changing climate patterns—major coconut producing and exporting countries researched this topic. In Sri Lanka, scientists developed a prediction tool that simulates annual coconut yield projections fifteen months in advance and has since applied these forecasts to estimate yields for the upcoming year (Fiondella, 2009). The simulation model (InfoCrop-coconut) may be another tool to help estimate coconut yield. This tool is derived from the generic InfoCrop tool that simulates annual tropical crops. InfoCrop-coconut is reported to have shown useful simulations for a range of agro-climatic zones (Kumar & Aggarwal, 2008).

Guyana's coconut industry could benefit from similar methods to evaluate and forecast climate change impacts on productivity. During dry seasons, rainfall monitoring for irrigation and fertilizer management interventions may be a temporary low-tech solution to support growers in maintaining yields. Research indicates that future climate scenarios may present an opportunity for increased yields once careful irrigation strategies are applied (Kumar & Aggarwal, 2013) along with other adaptation strategies.

Coconut producing areas along the coastal plain may see yields affected by saltwater intrusion and seasonal inundation under future climate. Spatial modeling of the hinterland regions (particularly Regions IX and X) indicates that climate variability will reduce suitable growing areas for this crop. However, coconut plantations may thrive with appropriate crop management and improved genetics. The palm is well adapted to high temperatures. Integrated pest management is a fundamental approach used by NAREI to protect coconut plantations. New coconut varieties from Mexico are being trialed to study how it adapts to the local climate and disease resistance (NAREI, 2018). In addition to exploring the use of appropriate perennial crop models for coconut, it may be worthwhile to undertake agronomic experiments that simulate future climate under irrigated conditions to understand how coconut cultivation can be expanded to crucial hinterland locations. Genetic adaptation measures such as converting to improved tall cultivars may also improve dry season tolerance and disease resistance.

4. Analysis

4.1. Spatial Analysis of Climate Variables

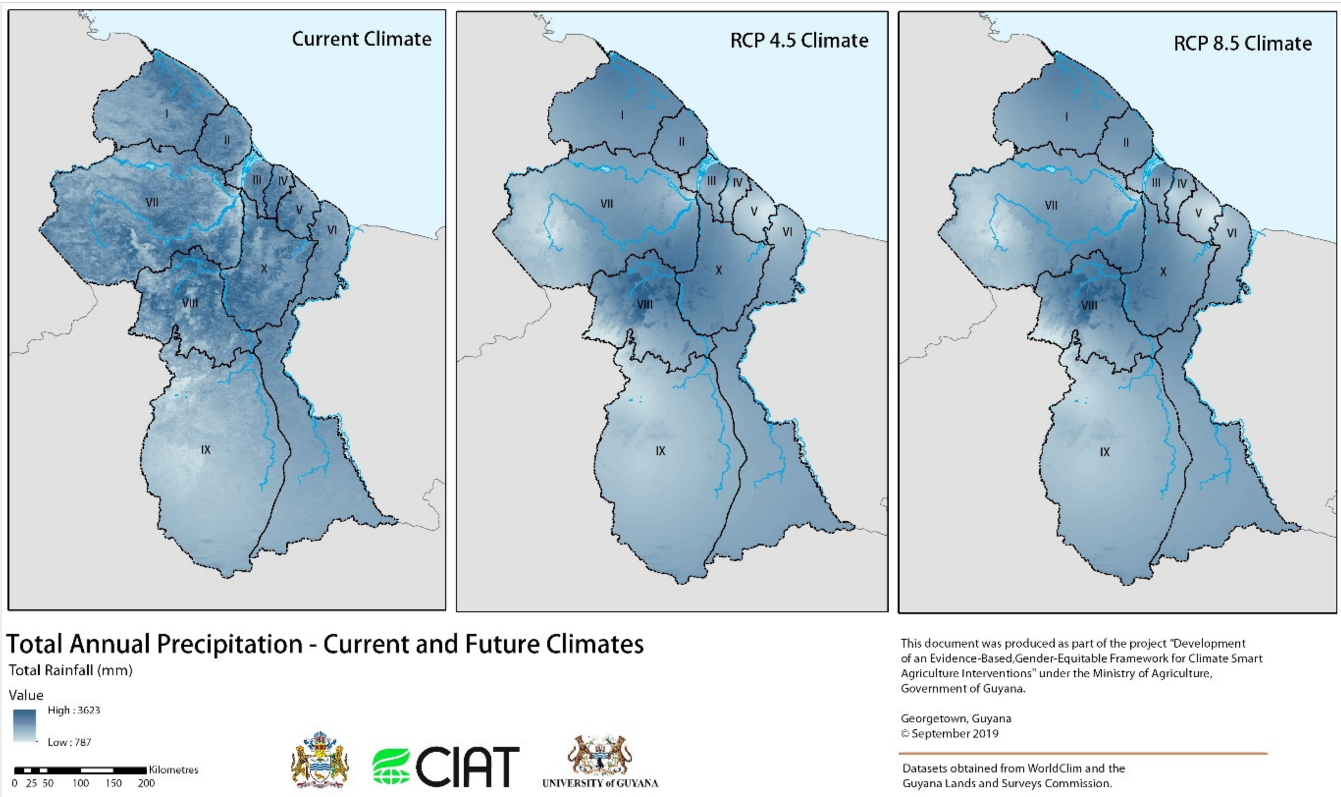

Figure 19 Guyana Total Annual Precipitation: Reference (left) and Future Climates.

The total annual precipitation range based on the current climate is 787-3307 millimeters. Under RCP4.5 and RCP8.5 climate scenarios, rainfall ranges are estimated at 839-3623 and 811-3480 millimeters, respectively. This indicates an overall increase in precipitation by 2050 by as much as 173 millimeters in some areas. Precipitation patterns are predicted to undergo a shift in distribution under future climates, with Regions V, VII, and IX receiving less rainfall. This phenomenon appears to be most pronounced in the important productive Mahaica/Mahaicony/Arbury (MMA) area at Region V. At Regions VII, particularly the upper Mazaruni, and throughout Region IX, reduced precipitation totals are likely to bring more intensive dry spells for indigenous communities that rely on subsistence and cash crop agriculture. Reduced precipitation is also likely at coastal Regions III and IV. Rainfall otherwise appears to increase in concentration at Region VIII in the future scenarios.

Temperatures across Guyana are generally expected to increase by 2050. The annual mean temperature range under the current climate is 16-27.8 °C. Under RCP4.5 and RCP8.5 climate scenarios, the mean temperature ranges are estimated at 15.7-29.8 °C and 16.5-30.6 °C. This indicates a probable overall increase by as much as 2.8 °C in some areas. Temperature is expected to intensify across all administrative regions and appears particularly pronounced in Region IX.

Examining the two climate variables suggests that most of Guyana are likely to experience increased temperatures and rainfall. The findings align with IPCC reports, indicating that flood risk is likely to be exacerbated by more frequent and extreme precipitation events (IPCC, 2014). Primary losses can be high in rural areas where most damage affects crops, livestock, and agriculture infrastructure. The coastal regions and savannah areas are at risk of more extreme weather events that can provoke severe flood and drought events. This presents a possible challenge for traditional farming areas and underscores the need to adopt new farming methods to build future resilience. Some of the crops studied under this project may thrive under future climate scenarios to sustain higher temperatures or are drought resistant. To better examine this, yield and spatial suitability estimates are summarized in the next section, focusing on the Regions under study.

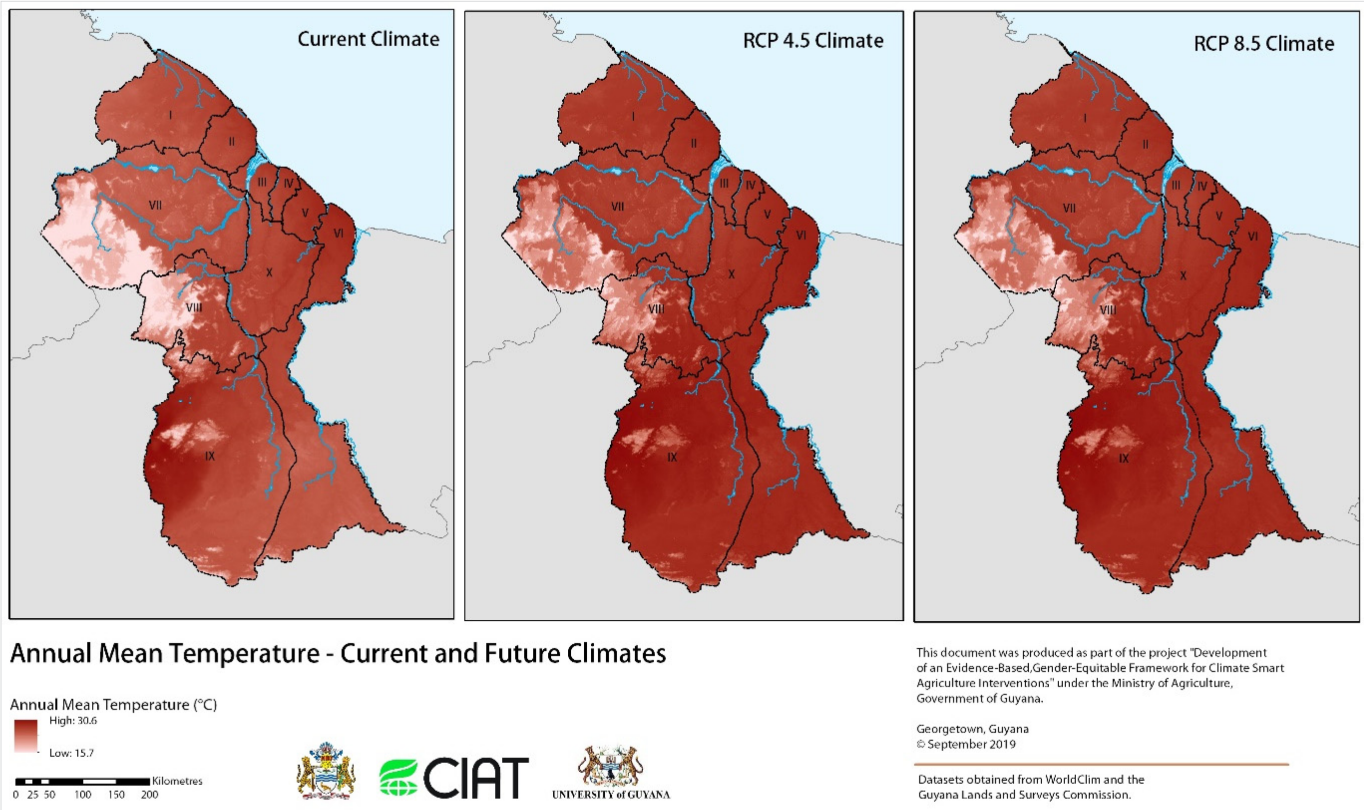

Figure 20 Guyana Annual Mean Temperature: Reference (left) and Future Climates.

4.2 Summary Analysis of Model Outputs

The crop and spatial models provide useful information for the agriculture sector regarding how these crops are expected to fare in the future. Focus is given to the potential of rice, plantain, pineapple, cassava, and sweet potato. Peanut and coconut were discussed in terms of spatial suitability only since crop modeling was not applied to estimate these crops' yield.

Crops	Future Yields	R9 Future Yields	Threats and Opportunities	Overall Rating*
Rice	Favorable	Favorable	Paddy bug infestation	High
Plantain	Favorable with successful disease management	Unfavorable in rainfed conditions, highly variable yield estimates under irrigated condition	Black Sigatoka	Medium
Pineapple	Favorable	Favorable under irrigated conditions		Medium
Cassava	Favorable	Favorable under irrigated conditions	Drought resistant, a new cultivar from Brazil, new possible areas for cultivation	Medium
Sweet Potato	Favorable	Favorable	Drought resistant, underutilized crop requiring weed control and pest and disease management	High

Table 5. Summary of future yields by crop.

***Overall Rating:**
High: Optimistic yields above the 1998-2018 reference period and future climate mean yields.
Medium: Favorable yields with irrigation measures and pest and disease management
Low: Poor yields under both rainfed and irrigated conditions, or below the 1998-2018 reference period.

Key findings from the crop model for future yield estimates suggest that:

- All crops are expected to persist at their traditional growing areas;
- Rice and sweet potato are expected to be most successful in future climate scenarios at both focus Regions and under rainfed and irrigated conditions;
- Pineapple and cassava return favorable yields at Region III under both irrigation scenarios;
- Irrigation will be needed for plantain, pineapple, and cassava cultivation at Region IX;
- Plantain cropping is not projected to do well in Region IX in the future climate scenarios;
- Land suitability for the climate is expected to increase for rice and cassava; and
- Suitability areas and levels will decrease for the remaining crops.

Yield	Region III	Region IX
Projected Increase	Rice Plantain Cassava	Rice Pineapple Sweet Potato Cassava
Projected Decrease	Pineapple	Plantain
No Major Change	Sweet Potato	

Table 6. Future yield by target region.

Land Suitability	Region III	Region IX
Projected Increase	Rice Cassava	Cassava Peanut
Projected Decrease	Plantain Coconut Pineapple* Sweet Potato	Rice Plantain Coconut Sweet Potato
No Major Change	Peanut	Pineapple

Table 7. Future land suitability by target region.

*Suitability level drops to moderate at the coastline.

Notably, an increase in suitable areas does not necessarily signal increases in yield. This has been seen in the returns from some of these models, such as sweet potato. Other factors such as irrigation, temperature, soil moisture, and crop pests and diseases can impact yield. Similarly, a decrease of suitable areas may not mean reductions in yield, as higher production levels can increase per hectare given the right environmental conditions and appropriate inputs through agricultural intensification.

4.3 Regional Outlooks

Essequibo-Islands-West Demerara (Region III)

Productive areas of Essequibo Islands-West Demerara (Region III) are situated on the coastal lowlands. Simultaneously, more in-depth sections of the Region are characterized by hilly sand and clay formations with some forested highland areas (Bernard, 1999). Most of the population is settled at coastal and island villages where rice farming dominates, along with coconut, sugar, and non-traditional crops that include cassava, sweet potato, pineapple, and plantain (Ministry of Agriculture, 2013). Coastal areas are below sea level, increasing hazard exposure to floods due to sea-level rise, saltwater intrusion from overtopping at conservancies, and sea defense breaches from tidal events. Increasing evapotranspiration rates, pests and diseases, and more severe and frequent dry spells have been problematic for Region III farmers in recent years.

The Region's climate is mainly influenced by the intertropical convergence zone (ITCZ) weather system. This results in biannual rainfall patterns that form two wet and two dry seasons. Increased temperatures are expected across the Region in the RCP4.5 and RCP8.5 climate models. At the same time, variable or reduced rainfall patterns could occur in the future. AquaCrop modeling of the selected crops estimates higher yields for rice cultivation, plantain, and cassava in future climate scenarios, and similar yields for sweet potato as are seen under current conditions. Pineapple cultivation is projected to experience a slight drop in yield. Suitable areas (under rainfed conditions) for rice and cassava cultivation are projected to increase, reducing arable land expected for the remaining crops as intensified temperature and precipitation will challenge productive yields.

More frequent or severe weather events such as spring tides, sea-level rise, saltwater intrusion, and dry spells could affect future yields at Region III. Crop pests and diseases in this Region have particularly challenged farmers. They will require mitigation under future drought conditions to guard against losses. Overall, the Region is expected to maintain productivity for most crops and can expect improved yields in the future with good field management.

Upper Takutu-Upper Essequibo (Region IX)

Region IX is the largest administrative region by area but carries a low population density. The western and northwestern areas of the Region are formed by its distinctive tropical grassland referred to as the Rupununi Savannahs. In contrast, mountainous areas (Kanuku Mountain Range and Acarai Mountains) are covered by riparian and semi-evergreen forests. The Rupununi Savannahs are a gently undulating plain about 100 to 165 above sea level. The Region comprises dispersed settlement characteristics of hinterland Guyana. Most of the population resides in the savannahs in over 80 communities. Amerindians comprise most of the population (86%) and are mainly of the Wapichan and Macusi tribes. Non-traditional crops targeted at this Region include peanut, cassava, and pineapple (Ministry of Agriculture, 2013).

Region IX is mainly exposed to flood and drought hazards associated with the annual wet and dry seasons. During periods of drought, Rupununi wet season tends to be shorter and the dry season longer. More severe instances of the annual flood event can isolate villages by submerging roads/trails and airstrips. Prolonged dry periods have been linked to severe food insecurity from high crop and livestock losses. At the same time, bush fires sometimes threaten villages during the dry season. Dry spells in the Rupununi have resulted in water shortages for irrigation as creeks and reservoirs dried up, and soil temperatures increased. Decreased root sizes or failed harvests have occurred at North Rupununi communities, such as Aranaputa and Surama, with the most recent severity recorded during the 2015 drought. Drought also escalates wildfires and pest infestations in the Region, threatening food security for some villages.

Savannah climate is classified as Tropical Wet and Dry (Aw), allowing for only one wet and dry season. The wet season often lasts about five (5) months from April to August, during which the majority of rain (about 80%) occurs. Temperatures are expected to intensify by about 1 °C at the North and South Rupununi Savannahs in the RCP4.5 and RCP8.5 climate models. Rainfall is projected to decrease across the Region, especially at the North Rupununi Savannahs. Therefore, prolonged dry spells and water stress are probable by 2050.

The crop models simulated for the selected crops indicate that crop yields are projected to increase for cassava, sweet potato, pineapple, and rice despite these conditions. The drought-resistant tuber crops should thrive under irrigated conditions, with cassava yields highest at Lethem and sweet potato yields highest at Karasabai. Both can withstand protracted periods of water stress and an associated reduction in growth and yields from increased temperatures and drought. Climate change may decrease the availability of productive areas across the Region, particularly for the cultivation of sweet potato, rice, and coconut. Higher temperatures and lower precipitation will not sustain crop growth under rainfed conditions. Plantain does not grow well in Region IX under current agro-climatic conditions, which is not expected to improve under future climate scenarios.

5. Conclusion

Model studies at administrative Regions III and IX generally project increased mean temperatures and reductions in total precipitation. Against the yield estimates from AquaCrop simulations, these results suggest that suitable arable land may decrease for many crops despite overall yield increases expected from the future climate. Predicted yield increases in future climate may materialize through agricultural intensification, focusing on inputs such as fertilizer, irrigation, and improved cultivars that are disease and drought-resistant.

Among the crops studied, rice and sweet potato are estimated to produce high yields in future climate scenarios at both Regions III and IX. Higher yields were returned than the 1998-2018 reference period, and both should thrive under rainfed conditions and be sustained by irrigation. For rice, one of the nation's traditional crops, yield and land suitability should rise at traditional growing areas and interior locations under climate change. The prospect of the future expansion of this crop into hinterland areas is promising for the sector, and improved rice varieties and irrigation techniques can help secure global rice industries (Bouman, n.d.). Sweet potato production can also sustain cash crop farmers in the future. However, crop pests and diseases threaten rice and sweet potato farming: the rice industry has struggled with paddy bug infestation, and sweet potato farmers require pest and disease management and weed control.

Cassava, pineapples, and peanuts are projected to perform reasonably well in future climate scenarios with acceptable field management practices. Plantain farming should be sustained on the coast in the future but is not expected to succeed in Region IX. Coconut farming should persist along the coast with climate-smart practices such as intercropping and integrated pest management. Future yield for coconut could not be modeled using the herbaceous crop models applied in this study. However, it requires a priority focus for predicting yield estimates. It is the third most cultivated crop in Guyana (Ministry of Agriculture, 2013). It may be at risk of future climate conditions. Genetic and agronomic adaptation to climate change can substantially benefit crop production that guards against some of these challenges. Among the priority crops, this is being pursued rice, sweet potato, and coconut. Although suitable areas under rainfed conditions are expected to decrease for most crops in both areas, higher yields are probable with agricultural climate adaptation that features adapted irrigation schedules, integrated pest and disease management, and improved varieties.

Pursuing an evidence-based approach to understanding how crops may persist in future climate scenarios is critical, as the threat to the agricultural sector is well established in national documents and related studies. Among Guyana's obligations to the United Nations Framework Convention on Climate Change (UNFCCC) is to prepare for climate change adaptation and develop appropriate agriculture (Government of Guyana, 2012). The Civil Defence Commission (CDC, 2014) noted the severe historical impacts of droughts and floods on Guyana's agricultural systems. Regional Risk Assessments were studied for each administrative region towards the development of Regional Disaster Risk Management Systems. The assessments considered the effects of natural hazards on agriculture. They emphasized the vulnerability of arable land to crop pests and diseases and flood and drought events. Narayan (2006) indicated that in coastal areas, increases in brackish water penetration of farmlands could impact the agricultural sector and displace populations severely.

These issues highlight the need for climate adaptation in the agricultural sector in the face of climate change and variability and focus on averting climate-induced land degradation to maintain productivity. The *National Strategy for Agriculture in Guyana 2013-2020* (Ministry of Agriculture, 2013) draws attention to two important details regarding agricultural land use:

- Only 11.5% of land in Guyana was being used effectively for agricultural purposes; and
- Non-traditional crops are expected to occupy more land in the future.

This Strategy places focus on agricultural diversification through the promotion of non-traditional crops such as coconut and pineapple. It emphasizes that agriculture forms a significant role in the nation's development outlook beyond food security to capture energy and agro-processing while supporting environmental sustainability. The attention placed on land use for improvements to agricultural systems, productivity, and expansion of non-traditional crops, underscore the importance of spatial suitability modeling in future climate scenarios.

In Guyana, land conversion of abandoned large-scale agricultural plots to residential and industrial uses has been stimulated by growing tenure needs within those land-use categories (Government of Guyana, 2013). The city of Georgetown and coastal urban zones is experiencing accelerated growth stimulated by the burgeoning oil and gas sector's economic transition. However, the *Green State Development Strategy: Vision 2040* stresses that traditional sectors must remain productive to safeguard a diversified and self-sufficient economy (Government of Guyana, 2019). Guyana's population, settlement, and economic profiles are expected to look quite different by 2040. They must prepare for urban expansion, but large-scale conversion of historically productive lands could impact the sector in the face of climate change. Guyana may become more reliant on supporting basic market needs if it is underprepared to produce food under future climate conditions. This adverse scenario could result in a prolonged period of food insecurity with far-reaching impacts on national development. Therefore, readiness and mitigation are vital in sustaining the agriculture sector against the severe impacts of climate change. This can be achieved through climate-smart interventions driven by targeted, integrative policies to secure farmers' livelihoods.

Moving forward, it is clear that achieving optimized production rates against land degradation issues of flooding, drought, and saline intrusion will be the central area of focus for the agriculture sector and local producers (Government of Guyana, 2007). It is also critical to examine and anticipate climate change impacts on indigenous communities (Colchester & La Rose, 2010) towards introducing appropriate and timely participatory interventions for those populations' food security. Situating the models against sectoral objectives can support policymaking by targeting crops at specific areas of the country, improving yields, and determining needed inputs and agricultural investments to ensure early adoption of climate-smart agricultural practices.

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